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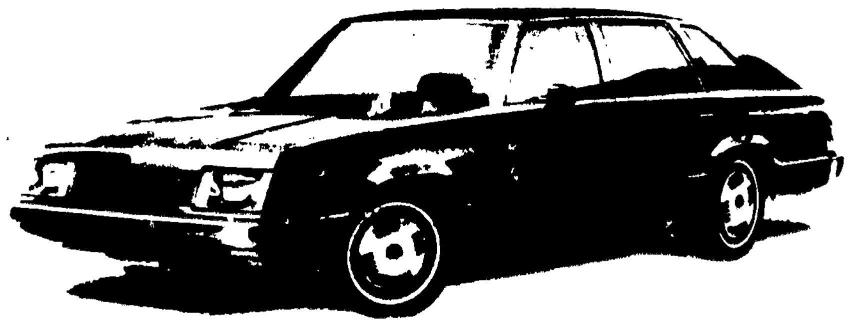
NEAR-TERM HYBRID VEHICLE PROGRAM

FINAL REPORT — PHASE I

Appendix D · Sensitivity Analysis Report



Contract No. 955190

Submitted to

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Submitted by

General Electric Company
Corporate Research and Development
Schenectady, New York 12301

October 8, 1979

GENERAL ELECTRIC

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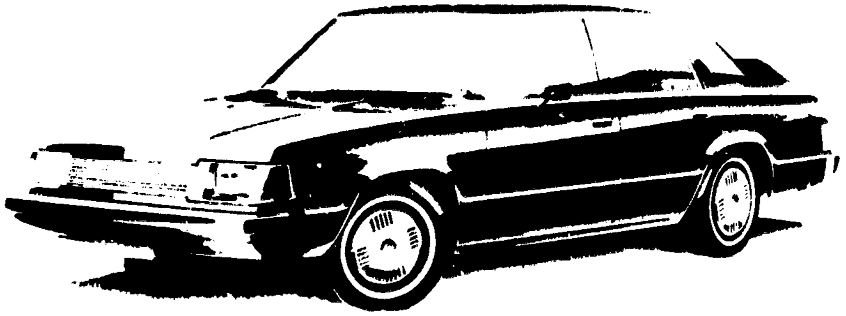

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FOREWORD

The Electric and Hybrid Vehicle (EHV) Program was established in DOE in response to the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976. Responsibility for the EHV Program resides in the Office of Electric and Hybrid Vehicle Systems of DOE. The Near-Term Hybrid Vehicle (NTHV) Program is an element of the EHV Program. DOE has assigned procurement and management responsibility for the Near-Term Hybrid Vehicle Program to JPL.

The overall objective of the DOE EHV Program is to promote the development of electric and hybrid vehicle technologies and to demonstrate the validity of these systems as transportation options which are less dependent on petroleum resources.

As part of the NTHV Program, General Electric and its subcontractors have completed studies leading to the Preliminary Design of a hybrid passenger vehicle which is projected to have the maximum potential for reducing petroleum consumption in the near term (commencing in 1985). This work has been done under JPL Contract 955190, Modification 3, Phase I of the Near-Term Hybrid Vehicle Program.

This volume is part of the Deliverable Item 7 Final Report of the Phase I studies. In accordance with Data Requirement Description 7 of the Contract, the following documents are submitted as appendices:

APPENDIX A is the Mission Analysis and Performance Specification Studies Report that constitutes Deliverable Item 1 and reports on the work of Task I.

APPENDIX B is a three-volume set that constitutes Deliverable Item 2 and reports on the work of Task 2. The three volumes are:

- Volume I -- Design Trade-Off Studies Report
- Volume II -- Supplement to Design Trade-Off Studies Report, Volume I
- Volume III -- Computer Program Listings

APPENDIX C is the Preliminary Design Data Package that constitutes Deliverable Item 3 and reports on the work of Task 3.

APPENDIX D is the Sensitivity Analysis Report that constitutes Deliverable Item 8 and reports on Task 4.

The three classifications - Appendix, Deliverable Item, and Task number - may be used interchangeably in these documents. The interrelationship is shown in the following table.

Appendix	Deliverable Item	Task	Title
A	1	1	Mission Analysis and Performance Specification Studies Report
B	2	2	Vol. I - Design Trade-Off Studies Report
			Vol. II - Supplement to Design Trade-Off Studies Report
			Vol. III - Computer Program Listings
C	3	3	Preliminary Design Data Package
D	8	4	Sensitivity Analysis Report

This is Appendix D, Sensitivity Analysis Report, which reports on Task 4 and is Deliverable Item 8. It presents the study methodology, the selection of input parameters and output variables, the sensitivity study results, and the conclusions of the sensitivity analysis.

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Section 1

INTRODUCTION AND SUMMARY

Section 1

INTRODUCTION

1.1 INTRODUCTION

This is Appendix D, Sensitivity Analysis Report (Deliverable Item 8). It reports on Task 4 and is part of Deliverable Item 7, Final Report, which is the summary report of a series which documents the results of Phase I of the Near-Term Hybrid Vehicle Program. This phase of the program was a study leading to the preliminary design of a five-passenger hybrid vehicle utilizing two energy sources (electricity and gasoline/diesel fuel) to minimize petroleum usage on a fleet basis.

The program is sponsored by the U.S. Department of Energy (DOE) and the California Institute of Technology, Jet Propulsion Laboratory (JPL). Responsibility for this program at DOE resides in the Office of Electric and Hybrid Vehicle Systems. Work on this Phase I portion of the program was done by General Electric Corporate Research and Development and its subcontractors under JPL Contract 955190.

This volume presents the study methodology, the selection of input parameters and output variables, the sensitivity study results, and the conclusions of the sensitivity analysis.

1.2 OBJECTIVES OF SENSITIVITY ANALYSIS (TASK 4)

The objective of Task 4 - Sensitivity Analysis - is to determine the impact of variations in selected parameters on the utility, the economic attractiveness, and the marketability of the hybrid vehicle. The parameters to be varied include travel characteristics, energy costs, hybrid vehicle lifetime, maintenance costs, and fuel economy of the Reference ICE Vehicle.

1.3 SUMMARY

The sensitivity studies were performed using the vehicle design computer program (HYVELD). All the results presented in this report pertain to the parallel hybrid configuration without secondary energy storage. The sensitivity of hybrid vehicle design to the power train configuration and component characteristics was reported in SRD-79-075, Design Trade-Off Studies Report, Volume I.

Results are presented for the effect on electric range requirements of changing the annual mileage statistics for the various missions. The effect of a ±7% change in annual mileage at a fixed electric range depends significantly on the percentile of travel on the electricity considered. Annual mileage has a significant effect on ownership cost, but it does not effect the differences in ownership cost between the hybrid and conventional vehicles. In general, the ownership costs increase slightly as a greater fraction of the total annual miles is driven in urban areas.

The price of electricity is relatively unimportant in determining the relative ownership costs of hybrid and conventional ICE vehicles. In contrast, the price of gasoline has a large effect on the relative ownership cost. Extending the lifetime and reducing the maintenance of the hybrid vehicle are important factors in attaining ownership costs less than those for conventional vehicles. The gasoline saved by the use of a hybrid vehicle increases linearly with annual mileage. The gasoline saved increases as more of the driving is done in urban areas. Gasoline savings are sensitive to the baseline fuel economy of the Reference ICE Vehicle. Marketability and fraction of gasoline saved are not sensitive functions of electric range at least in the neighborhood of a 30-mi nominal range.

1.3.1 CONCLUSIONS

The major conclusions drawn from the sensitivity analysis are the following:

1. Changes in annual mileage are reflected directly in the fraction of the miles that the hybrid vehicle can be driven primarily on electricity with the marginal effect increasing rapidly when the fraction falls below 50%.

2. For the lowest cost dc electric drive system and high-volume production, the initial cost of the hybrid vehicle would be \$1200 to \$1500 higher than that of the conventional vehicle. This cost differential would be \$1600 to \$2100 for low-volume production of the electric components.

3. For nominal energy costs (\$1.00/gal for gasoline and 4.2¢/kWh for electricity), the ownership cost of the hybrid vehicle is projected to be 0.5 to 1.0¢/mi less than the conventional ICE vehicle. To attain this ownership cost differential, the lifetime of the hybrid vehicle must be extended to 12 years and its maintenance cost reduced by 25% compared with the conventional vehicle.

4. The ownership cost advantage of the hybrid vehicle increases rapidly as the price of fuel increases from \$1 to \$2/gal. The effect of the cost of electricity on ownership cost is small for electricity prices between 2.5¢ and 8.5¢/kWh.

5. Annual mileage and fraction of miles in urban driving do not significantly affect the ownership cost differential between the hybrid and conventional vehicles.

6. Changes in general economic conditions (i.e., the inflation rate) do not significantly affect the ownership cost differential between the hybrid and conventional vehicles.

7. Annual fuel savings using the hybrid vehicle are strongly dependent on the fuel economy baseline used for the Reference ICE Vehicle. Using projected 1985 fuel economy values, the hybrid vehicle would have a fuel savings of about 55% or 250 gal per vehicle.

8. Hybrid vehicles would be economically attractive to a wide group of new car buyers with the ownership cost and fraction of fuel saved varying only slightly between the 35th and 90th percentile of car owners.

9. The economic attractiveness of the hybrid vehicle is not a strong function of design electric range for changes in range between 30 to 40 mi.

10. Hybrid vehicles using diesel engines have a slight advantage in ownership cost (0.5 - 1.0¢/mi) compared to those using gasoline engines, but the gasoline engine-powered hybrid has a slightly greater ownership cost differential advantage compared to the corresponding conventional vehicle.

Section 2

STUDY METHODOLOGY

2.1 INTRODUCTION

The Mission Analysis (Task 1) and Design Trade-Off Study (Task 2) results[1,2] correspond to a set of nominal values for travel characteristics, energy costs, general economic conditions, hybrid vehicle lifetime and maintenance, and fuel economy of the reference ICE vehicle. The nominal values used in Task 1 and Task 2 were best estimates of the various parameters, but, without question, there is considerable uncertainty regarding some of the parameters.

This study (Task 4) is concerned with the impact of varying selected parameters around the nominal values (i.e., higher and lower). The impacts of particular interest are the utility of the hybrid vehicle, its economic attractiveness and marketability, and the fuel saved relative to the reference ICE vehicle. Some of the parameters selected for study were specified by the Jet Propulsion Laboratory (JPL) in the work statement for Task 4.[3] Others were included in the sensitivity study because the work in Tasks 1 and 2 indicated their impact would be particularly significant.

The approach used and the scope of the sensitivity study performed are discussed in the following sections for the parameters related to Mission Analysis and Design Trade-Off Studies.

2.2 MISSION ANALYSIS-RELATED STUDIES

The methodology used in the mission analysis-related sensitivity studies was the same as that used to obtain the results presented previously.[1] The method requires data on annual mileage. However, there is considerable uncertainty regarding such data. Therefore, the sensitivity of the changes in hybrid vehicle range requirements to changes in annual mileage was studied by assuming a ± 7% variation in the annual mileage statistical distributions[1] (see Figure 2-1). The results of the trip-characteristic computer calculations for the stated variations in annual mileage are given in Tables 2-1 and 2-2 for the various missions.

It is of interest to compare the annual mileage distributions used in the present study with some recent data published by U.S. News and World Report (USNWR).[4] This is done in Figure 2-2 using the all-purpose mission curves from Figure 2-1 because the all-purpose mission most closely matches the general character of the responses to the USNWR questionnaire. The agreement between the new data and that used in the present study is quite good.

Table 2-1

SENSITIVITY OF DAILY TRAVEL DISTANCES INSIDE SMSAs FOR VARIOUS MISSIONS

Mission	Nominal* Annual Distance (Miles)	Nominal* Daily Distance (Miles) Percentile⁺ 50	75	90	+ 7% Annual Distance (Miles)	+ 7% Daily Distance (Miles) Percentile⁺ 50	75	90	- 7% Annual Distance (Miles)	- 7% Daily Distance (Miles) Percentile⁺ 50	75	90
Personal Business Only												
50th Percentile	3,000	20	29	39	3,200	22	31	42	2,800	19	28	38
75th Percentile	4,500	25	38	49	4,800	27	41	51	4,200	24	37	48
90th Percentile	6,500	32	49	66	7,000	35	52	71	6,000	31	48	64
Personal Business Plus Work Trips												
50th Percentile	6,625	21	32	43	6,825	22	34	45	6,425	20	29	42
75th Percentile	8,125	26	39	57	8,425	28	42	60	7,825	24	38	55
90th Percentile	10,125	32	51	76	10,625	34	55	80	9,625	30	49	72
All Purpose (Excluding Intercity Travel)												
50th Percentile	6,400	34	52	69	6,800	36	54	73	6,000	31	50	67
75th Percentile	9,200	52	74	99	9,800	55	77	>100	8,600	47	70	95
90th Percentile	11,600	>100	>100	>100	12,400	>100	>100	>100	10,800	88	94	>100
All Purpose (Including Intercity Travel)												
50th Percentile	7,000	36	61	>100	7,500	37	64	>100	6,500	34	57	90
75th Percentile	11,300	50	84	>100	12,100	52	87	>100	10,500	48	78	>100
90th Percentile	17,000	70	>100	>100	18,200	72	>100	>100	15,800	67	>100	>100

*Nominal refers to data used in initial mission analysis as reported in Near-Term Hybrid Vehicle Program: Mission Analysis and Performance Specification Studies Report (General Electric Report No. SRD-79-010). Plus and minus seven percent refers to increase and decrease in annual mileage compared to the nominal.

⁺Percentiles are for vehicle miles.

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Table 2-2

SENSITIVITY OF DAILY TRAVEL DISTANCES OUTSIDE SMSAs FOR VARIOUS MISSIONS

Mission	Nominal*				+ 7%				- 7%			
	Annual Distance (Miles)	Daily Distance (Miles) Percentile+			Annual Distance (Miles)	Daily Distance (Miles) Percentile+			Annual Distance (Miles)	Daily Distance (Miles) Percentile+		
		50	75	90		50	75	90		50	75	90
Personal Business Only												
50th Percentile	4,400	25	39	52	4,700	27	41	57	4,100	24	36	50
75th Percentile	6,500	31	49	67	7,000	35	52	72	6,000	30	48	63
90th Percentile	9,300	43	64	82	9,900	45	65	87	8,700	41	62	80
Personal Business plus Work Trips												
50th Percentile	6,275	23	36	54	6,575	25	38	56	5,975	22	34	49
75th Percentile	8,375	31	49	68	8,875	33	50	71	7,875	29	45	64
90th Percentile	11,175	42	64	93	11,775	44	66	93	10,575	39	59	82
All Purpose (Excluding Intercity Travel)												
50th Percentile	7,800	40	62	83	8,300	44	65	89	7,300	39	58	80
75th Percentile	10,600	61	90	>100	11,300	68	94	>100	9,900	59	84	>100
90th Percentile	12,700	>100	>100	>100	13,600	>100	>100	>100	11,800	>100	>100	>100
All Purpose (Including Intercity Travel)												
50th Percentile	9,000	43	72	>100	9,600	45	76	>100	8,400	41	68	>100
75th Percentile	13,700	58	>100	>100	14,700	62	>100	>100	12,700	57	93	>100
90th Percentile	20,[illegible]	84	>100	>100	21,900	88	>100	>100	19,100	76	>100	>100

*Nominal refers to data used in initial mission analysis as reported in Near-Term Hybrid Vehicle Program: Mission Analysis and Performance Specifications Studies Report (General Electric Report No. SRD-79-010). Plus and minus seven percent refers to increase and decrease in annual mileage compared to the nominal.

+Percentiles are for vehicle miles.

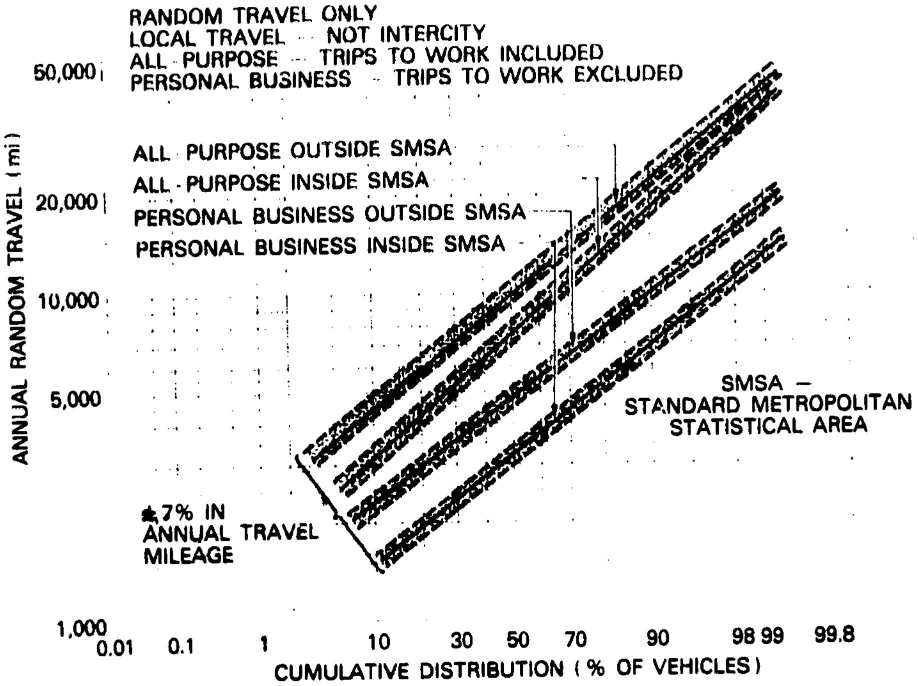


Figure 2-1. Annual Random Travel Mileage Characteristics

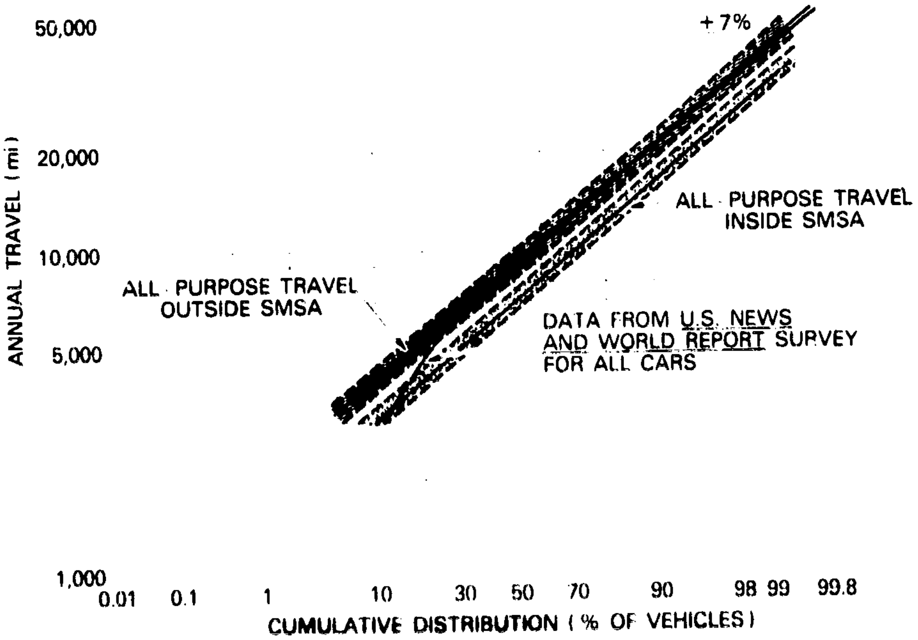


Figure 2-2. Annual Travel Mileage Characteristics

2.3 RELATED DESIGN TRADE-OFF STUDIES

These sensitivity studies dealt with determining the impact of variations of travel characteristics, energy costs, general economic conditions, hybrid vehicle lifetime and maintenance costs, and fuel economy of the reference ICE vehicle on the utility of the hybrid vehicle, its economic attractiveness and thus, its marketability, and the fuel saved relative to an ICE vehicle. The sensitivity studies were performed using the Hybrid Vehicle Design (HYVELD) computer program which was also employed extensively in Task 2. A Fortran listing of HYVELD is given in Volume III.(2) HYVELD was developed so that most of the important parameters on which the vehicle design and economics depend could easily be changed by simply altering the inputs to the program. The versatility built into HYVELD made performing the parametric studies discussed herein quite straightforward and fast.

A summary of the parameter sensitivities studied using HYVELD is given in Table 2-3. About 50 runs were made - divided into the groups indicated - to investigate the effect of one or, at most, three parameters at a time. The manner in which the parameters were varied is discussed in Section 3. All the results presented in this report pertain to the parallel hybrid configuration (without secondary energy storage) and are for a power-to-weight ratio Kp equal to 0.02 kW/lb. The sensitivity of hybrid vehicle design to power train configuration and component characteristics was studied in detail in Task 2(2) and was not repeated in this study (Task 4). The HYVELD calculations yielded parametric results for other hybrid/electric vehicle configurations, but those results are not discussed in this task because the design trade-off studies indicated clearly that the parallel hybrid approach was far superior to the others. Thus, it is the sensitivity of the parallel hybrid results to the parametric variations that is of prime importance.

Table 2-3

SUMMARY OF PARAMETER SENSITIVITIES
STUDIED USING HYVELD

Sensitivity to	Parameters Varied	Number of Combinations
Energy Costs	Gasoline Price, Electricity Price	8
Annual Mileage	Annual Mileage	4
Fraction of mileage in City	Fraction of Mileage in City	4
Economic Conditions	Discount Rate, Interest Rate, Inflation Rate	3
Vehicle Lifetime and Maintenance Improvement	Vehicle Lifetime, Additional Cost Factor to Extend Life, Maintenance Improvement Factor	8
Percentile of Vehicle Random Travel	Annual Mileage, Fraction of Mileage in City, Vehicle Electric Range	12
Engine Type	Engine Type (Diesel and Gasoline), Diesel Fuel Price	4
Reference ICE Vehicle Fuel Economy	Urban and Highway Fuel Economy of the ICE Vehicle	3
Electric Drive-line Component Costs	Specific Cost of Each Electric Drive-line Component for Low and High Production Rates	6

Section 3

SELECTION OF INPUT PARAMETERS AND OUTPUT VARIABLES

Section 3

SELECTION OF INPUT PARAMETERS AND OUTPUT VARIABLES

In any sensitivity analysis, there are input parameters which are varied systematically and output variables or functions on which the effect of altering the input parameters is to be determined. In the present study, the input variables are the following:

1. Travel Characteristics
   - Annual mileage
   - Fraction of miles in city driving
   - Daily travel statistics
2. Energy costs
   - Gasoline and diesel fuel price
   - Electricity price
3. Vehicle lifetime and maintenance costs
   - Effective lifetime of the hybrid vehicle
   - Fractional reduction of maintenance costs relative to a conventional vehicle
4. General economic conditions
   - Discount rate
   - Interest rate
   - Inflation rate
5. Fuel economy of the Reference ICE Vehicle
   - Miles per gallon in city driving
   - Miles per gallon in highway driving
6. Drive-line component costs
7. Engine type

The output variables or functions which are determined for the combinations of input parameters are the following:

1. Electric range requirement
2. Initial cost of the vehicle
3. Ownership cost
4. Fraction of fuel saved or annual fuel saving
5. Market penetration

The input parameters which will be varied and the range of values used are discussed in Section 3.1. The output variables and how they are related to the input parameters are discussed in Section 3.2.

3.1 SELECTION OF INPUT PARAMETERS

3.1.1 TRAVEL CHARACTERISTICS

3.1.1.1 Annual Mileage

Annual mileage is an important parameter for at least two reasons. First, it has a strong influence on daily travel statistics and, thus, on the fraction of miles that the hybrid vehicle can be operated primarily on electricity. Secondly, the annual mileage influences directly the effect of fixed costs on operating cost and the total annual fuel consumption of both the hybrid and conventional vehicles. Annual mileage statistics are given in Figure 2-1 for various missions and localities. Average annual mileage values were specified by the Jet Propulsion Laboratory as follows:

- Low - 11,022
- Medium (nominal) - 11,852
- High - 12,682

In all sensitivity calculations in which annual mileage was not the input parameter under study, the nominal annual mileage of 11,852 was used.

3.1.1.2 Fraction of Miles in City Driving

Since the hybrid vehicle utilizes primarily electricity in urban driving, the fraction of miles driven in the city is an important factor influencing both operating cost and energy usage. For purposes of a fuel economy projection, the Environmental Protection Agency (EPA) uses a city/highway mileage split of 55/45. Analysis of available travel data(1) indicates that for areas within Standard Metropolitan Statistical Areas (SMSAs) a city/highway mileage split of 65/35 was more appropriate. As a result, the 65/35 split was adopted as nominal for the present hybrid vehicle study. In the sensitivity analysis, the fraction of miles in city driving was varied as follows:

- Low - 0.55
- Nominal - 0.65
- High - 0.75

3.1.1.3 Daily Travel Statistics

The designation "daily travel statistics" means either the fraction of days or the fraction of miles driven on days in which the total mileage on that day is less than a specified value. This is conveniently expressed as "accumulative probability distributions," as shown in Figures 3-1, 3-2, and 3-3.(1) Daily travel statistics are an input quantity when one is considering the fraction of miles that can be driven on electricity but can

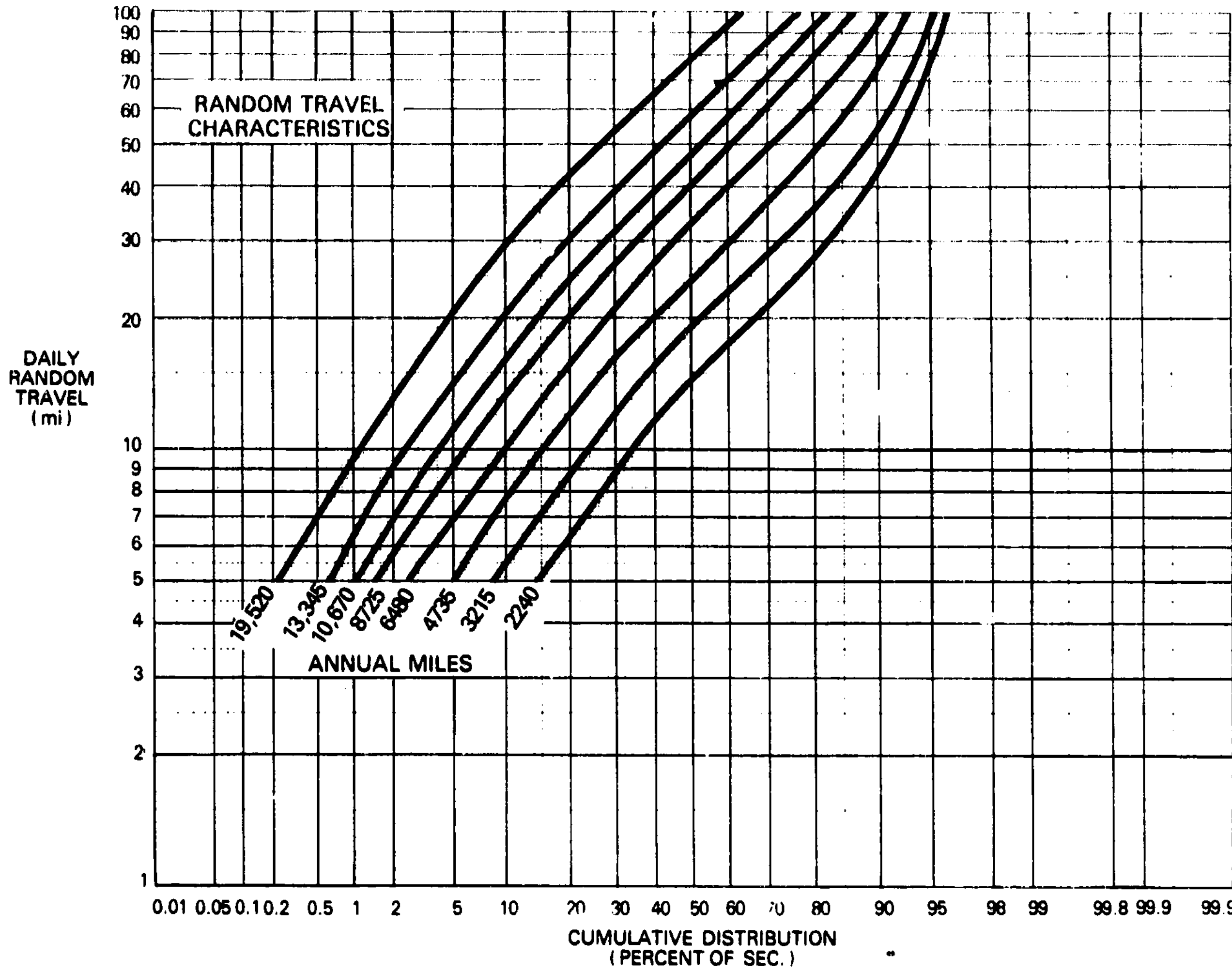


Figure 3-1. Daily Random Travel for All Travel - Percent of Vehicle Miles - as a Function of Annual Miles

be an output quantity when one is considering the effect of annual mileage. Daily travel statistics are utilized in the present study to investigate the effect of vehicle electric range on ownership cost and gasoline saved by potential car buyers in stated percentiles of auto use (annual mileage). The sensitivity of hybrid vehicle economic attractiveness to percentile of auto use is an indicator of the possible market penetration of a particular hybrid vehicle design. For this purpose, the daily statistics given in Figure 3-3 have been converted in Table 3-1 to the following inputs for the sensitivity analysis.

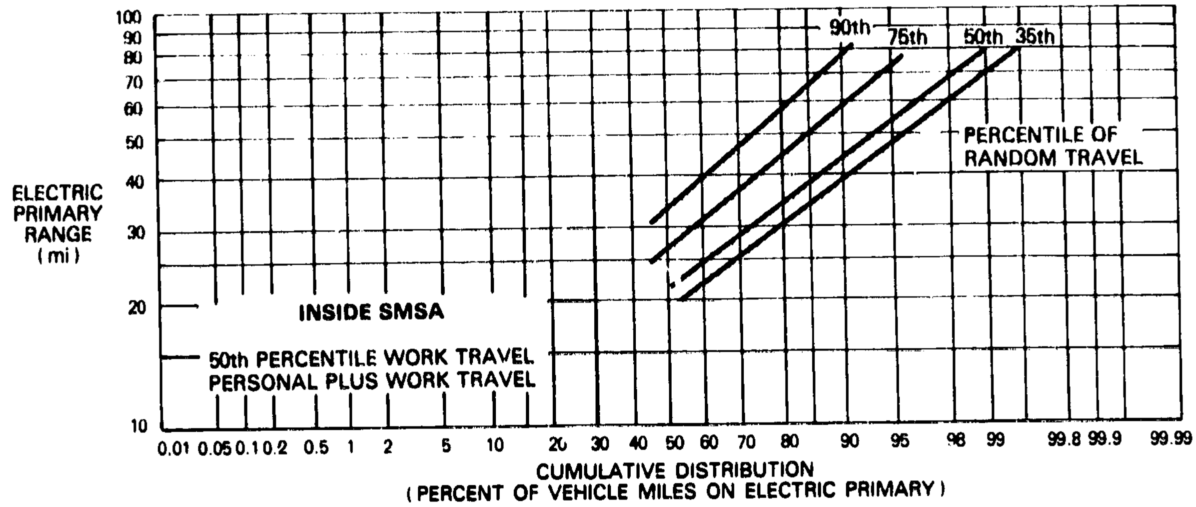


Figure 3-2. Effect of Vehicle Range on Vehicle Use - Percent of Vehicle Miles, Inside SMSA, Personal Plus Work Travel

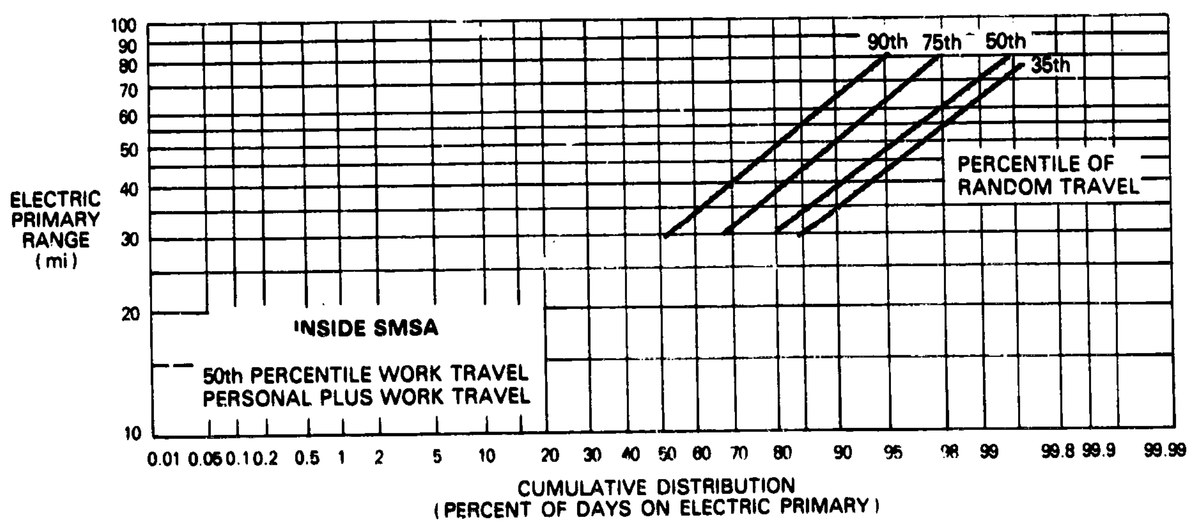


Figure 3-3. Effect of Vehicle Range on Vehicle Use - Percent of Days, Inside SMSA, Personal Plus Work Travel

Table 3-1

VEHICLE USE SENSITIVITY INPUTS

Total Annual Miles	Urban Miles	Percentile of Use \ Electric Primary Range	Fraction of Miles on Electricity in Urban Driving 30 mi	35 mi	40 mi
8,571	6,000	35	0.79	0.86	0.905
9,714	6,800	50	0.72	0.81	0.865
11,860	8,300	75	0.57	0.66	0.74
14,715	10,300	90	0.43	0.53	0.61

3.1.2 ENERGY COSTS

There are three energy costs of interest in the present study:

- Gasoline price
- Diesel fuel price
- Electricity price

Energy costs have a direct impact on the operating costs of both hybrid and conventional vehicles, but the impact of rising petroleum fuel costs on the hybrid vehicle is less than for the conventional vehicle. Hence, the hybrid vehicle becomes more economically attractive as fuel prices increase. Energy costs in 1985 were specified by the Jet Propulsion Laboratory. Those values were used directly, but he range of values was extended as shown in Table 3-2 below to account for the accelerated rise in energy costs in recent months.

Table 3-2

ENERGY COSTS

Energy	Unit	Low	Nominal	High	Extreme
Electricity	¢/kWh	3.80	4.20	5.50	7.50
Gasoline	$/gal	0.67	0.96	1.24	2.50
Diesel	$/gal	0.60	0.89	1.15	2.50

In the HYVELD program, diesel fuel is treated in terms of its gasoline equivalent by energy content. Thus, the diesel unit price shown in the table is reduced by a factor of 1.15 to get the equivalent price of gasoline (e.g., a diesel fuel price of $1/gal is equivalent to $.87/gal for gasoline).

3.1.3 VEHICLE LIFETIME AND MAINTENANCE COSTS

Vehicle lifetime is an important factor in determining the depreciated value of the vehicle as it ages. Nonlinear depreciation (reverse sum of the digits method) was assumed using the relationship

$$DPV = \left[1 - \frac{\sum_{i=0}^{N-1} (NL - i)}{\sum_{i=1}^{NL} i} \right] (OC)$$

where

DPV - depreciated value after N years

NL - vehicle lifetime

OC - original vehicle cost

In this sense, vehicle lifetime is the period of time over which the vehicle has resale value significantly above a scrap price. In this study it was assumed that the lifetime of a conventional ICE vehicle was 10 yrs and that of the hybrid vehicle was varied between 10 and 15 yrs. In order to extend the lifetime of the hybrid vehicle, an additional cost was included for special treatment of the body and other structural parts. The vehicle improvement cost factor (VICF) was taken to vary between 5 and 10% depending on the lifetime extension desired.

The maintenance cost of the hybrid vehicle (MCHV) was expressed relative to that of the conventional ICE vehicle as

$$MCHV = (1 - MIFHV)\ MCCV$$

where MIFHV is the maintenance improvement factor used for the hybrid vehicle. MIFHV was varied between 0 and 50%. The maintenance cost (MCCV) of the conventional vehicle was taken as 2¢/mi.

Computer runs were made for the following combinations of vehicle lifetime and maintenance cost parameters.

NL	MIFHV	VICF
10	0	0
10, 15	0	0.05
10, 12	0.25	0.05
10, 12	0.50	0.05
15	0.50	0.10

3.1.4 GENERAL ECONOMIC CONDITIONS

The general economic conditions are described in terms of the inflation rate (IF), interest rate (IR), and discount rate (DR). Both the discount rate and interest rate increase as the rate of inflation increases. Calculations were made for the following combinations of economic factors.

	Low	Nominal	High
Inflation Rate (%)	3	5	10
Discount Rate (%)	5	7	13
Interest Rate (%)	8	10	15

3.1.5 FUEL ECONOMY OF THE REFERENCE ICE VEHICLE

Both the economic attractiveness of the hybrid vehicle and the fuel (gasoline or diesel) saved depend strongly on the fuel economy assumed for the Reference ICE Vehicle. There is considerable uncertainty regarding the 1985 fuel economy of five-passenger ICE vehicles because it is not known what EPA fuel economy ratings such vehicles will have in 1985, and, in addition, the magnitude of the discrepancy between EPA ratings and actual on-the-road fuel economy cannot be accurately predicted. In the present study the fuel economy projections developed in the Mission Analysis Task(1) were used and the correction factor recommended by the Jet Propulsion Laboratory was assumed to apply in 1985.

$$(FE)_{COR} = 0.71\ (FE)_{EPA} + 2.83$$

Sensitivity calculations were made for both 1979 and 1985 fuel economy values (corrected and uncorrected) for gasoline engine-powered hybrid vehicles and for 1985-corrected fuel economy values for diesel engine-powered hybrid vehicles. The fuel economy values used in the sensitivity studies for city and highway driving are listed in Table 3-3 for gasoline and diesel engines.

Table 3-3

FUEL ECONOMY VALUES

Engine Type	Fuel Economy (mpg)		Year
	City	Highway	
Gasoline	19	28	1979
Gasoline	17	23	1979 - Corrected
Gasoline	28	42	1985
Gasoline	22	32	1985 - Corrected (nominal)
Diesel	29 (25.5*)	40 (35*)	1985 - Corrected

*Gasoline equivalent

3.1.6 ELECTRICAL DRIVE-LINE COMPONENT COSTS AND ENGINE TYPE

For the most part the sensitivity parameters discussed in previous sections did not deal with the technology of the hybrid power train, i.e., the characteristics of the drive-line components. A limited number of results are given in this report showing the effect of several electrical drive options and the diesel engine on the initial cost of the hybrid vehicle and its ownership cost. This is done so that the relative magnitudes of the effects of the social/economic factors and the technical inputs can be compared and assessed. The component cost characteristics used in the sensitivity study are given in Table 3-4. Note that specific cost ($/kW) are given for a low production rate (100,000 units/yr) and a high production rate (1,000,000 units/yr). The latter production rate corresponds to that in the United States auto industry. It has been assumed that for the hybrid vehicles to attain the desired market penetration and resultant significant fuel savings (millions of barrels/day), component production rates comparable to those for conventional vehicles are required. The costs corresponding to those high production rates were taken as the nominal values in the sensitivity study calculation.

Table 3-4

DRIVE-LINE COMPONENT COST CHARACTERISTICS

	Cost ($/kW)* (Production Rate**)	
	High	Low
DC - Armature and Field Control		
• Motor	20.0	30.0
• Controller	14.1	21.0
DC - Battery Switching and Field Control		
• Motor	20.0	30.0
• Controller	6.7	10.0
AC - Induction Motor and Inverter		
• Motor	13.3	20.0
• Inverter	19.0	28.5
Engine Type		
• Gasoline	8.5	——
• Diesel	10.5	——

*All costs in $/kW; electric motors costed at continuous power rating; all others at peak power rating

**High production rate is 1,000,000 units/yr. Low production rate is 100,000 units/yr.

3.2 OUTPUT VARIABLES

3.2.1 ELECTRIC RANGE REQUIREMENT

The electric range requirement of the hybrid vehicle is one of the most important design parameters. For the parallel hybrid, this requirement sizes the battery pack in most cases and has an important impact on both the initial cost of the vehicle and its ownership cost. The nominal requirement is that the electric range of the hybrid be great enough so that at least 75% of the urban miles can be driven using the electric drive system as primary. This would permit a savings of about 75% of the fuel used by the conventional ICE vehicle in city driving and would also have a favorable impact on the economics of hybrid vehicle operation.

3.2.2 INITIAL VEHICLE COST

One of the requirements in the Near-Term Hybrid Vehicle Program is that the initial cost of the hybrid vehicle be comparable to that of the conventional ICE vehicle. This has been interpreted to mean that the incremental initial cost of the hybrid should not be so great as to discourage, in itself, potential new car buyers from purchasing the hybrid vehicle. Therefore, the sensitivity of the initial cost to travel characteristics, economic factors, and component cost is a key consideration.

3.2.3 OWNERSHIP COST

Since the initial cost of the hybrid vehicle will undoubtedly be higher than that of the conventional ICE vehicle, it is critical that its life-cycle cost ($/mi) be less than that of the conventional vehicle. The term "ownership cost" means the total cost of ownership pro-rated over each mile of use of the vehicle. In the present study ownership cost includes both fixed costs, such as vehicle depreciation, insurance, registration, etc., and variable costs such as battery replacement, electricity cost, fuel cost, maintenance cost, etc. Ownership cost is a complicated function of many of the input parameters discussed in Section 3.1. Hence, detailed comparison of the relative effects of various parameters on the ownership costs of the hybrid and conventional vehicle is probably the most important part of the sensitivity analysis task.

The ownership costs calculated in this study are those of the first owner of the hybrid vehicle and have been averaged over the first four years of its life. It was assumed that if the life cycle costs of the hybrid vehicle were attractive to the first owner, market penetration would be satisfactory and the resale of the vehicle to the second owner would present no difficulties.

3.2.4 FUEL SAVING (Total and Fraction)

Since the primary objective of utilizing hybrid vehicles for personal transportation is to save petroleum fuels, the sensitivity of fuel savings to the various input parameters is clearly of extreme interest. Fuel savings depend strongly on travel characteristics, as well as the fuel use characteristics of both the hybrid conventional ICE vehicles. Fuel savings are calculated directly by the HYVELD program so that determination of the sensitivity of fuel savings to changes in the various input parameters presented no difficulty.

3.2.5 MARKET PENETRATION

Assessing market penetration in a quantitative manner is probably the most difficult problem associated with the Near-Term Hybrid Vehicle Study. It is relatively simple to identify circumstances which would preclude significant market penetration and to identify other situations which would result in very rapid penetration of hybrid vehicles into the passenger-car market. Neither of the extreme cases appear probable in the near-term based on the results of the Mission Analysis and Design Trade-Off Tasks.[1,2] The projected situation seems to be that for the nominal values of the input parameters the initial cost of the hybrid vehicle will be about $1500 higher than that of the conventional ICE and that by using lead-acid batteries the ownership cost of the hybrid vehicle will be equal to or slightly lower than the conventional vehicle. This means that the break-even price of gasoline is about $1/gal for the hybrid vehicle. From the viewpoint of the average car buyer, then, there is no clear-cut reason why he/she should buy a hybrid vehicle rather than a conventional vehicle based on the nominal set of input parameters. The results of the sensitivity studies will be used to assess how changes in the nominal set of circumstances will influence market penetration and how the statistical character of auto usage affects the attractiveness of hybrid vehicles to segments of the auto market.

Section 4

SENSITIVITY STUDY RESULTS

Section 4

SENSITIVITY STUDY RESULTS

4.1 ELECTRIC RANGE REQUIREMENTS

The effect on electric range requirements of changing the annual mileage statistics for the various missions - both inside and outside Standard Metropolitan Statistical Areas - by ±7% is shown in Figures 4-1 through 4-4. The same results were given previously in Section 2.2 in tabular form (see Table 2-1). It is of interest to analyze the effect of the ±7% variation in annual mileage at a fixed percentile of miles traveled primarily on electricity (e.g., along a vertical line in Figure 4-1) and for a fixed design electric range (e.g., along a horizontal line in Figure 4-1). The effect of a ±7% variation in annual mileage statistics on the electric range requirement for 75% of daily travel on electricity is shown in Figure 4-5 as a function of the percentile of cars used for personal and work travel. Figure 4-5 indicates that in this case the ±7% variation in annual mileage results in a corresponding ±7% change in electric range requirement at each percentile of the auto population.

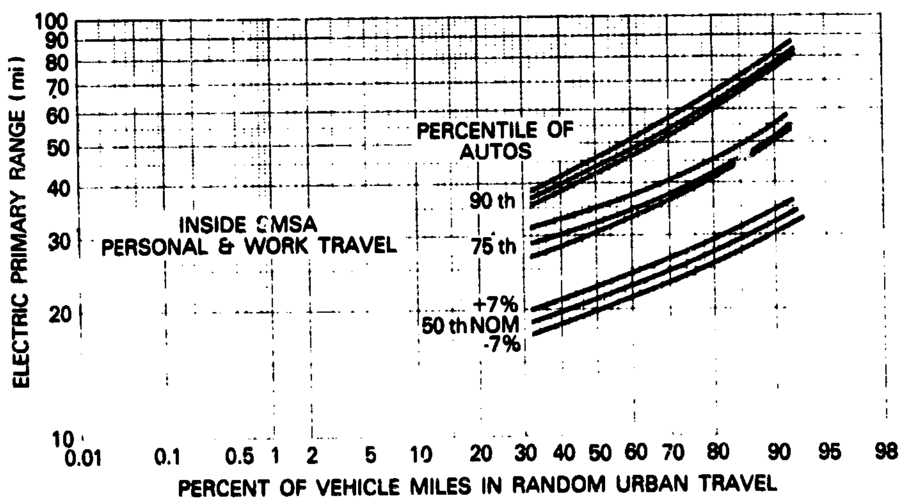


Figure 4-1. Effect of Vehicle Range on Vehicle Use - Percent of Random Miles Traveled, Inside SMSA, Personal Plus Work Travel

It can also be observed from Figures 4-1 through 4-4 that the effect of a ±7% change in annual mileage at a fixed electric range depends significantly on the percentile of travel on electricity being considered. For high expected percentiles of travel (≥ 75%) on electricity a ±7% variation in annual mileage has only a small effect, but for lower expected percentiles (< 50%) of travel on electricity, the effect of the ±7% variation is much greater. For example, for a primary electric range of 30 mi with cars in the 75th percentile of use based on annual random travel (miles), a ±7% change in annual mileage results in the percentage of travel

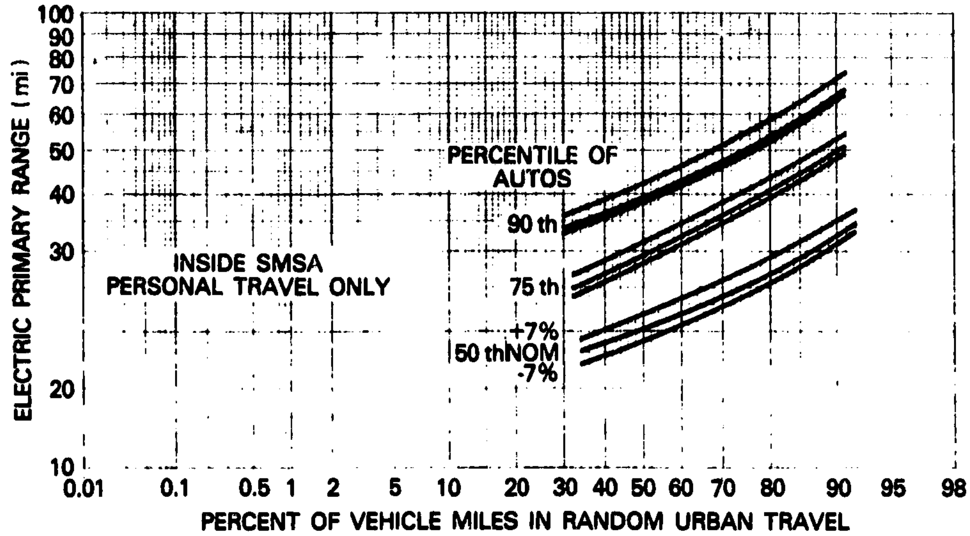


Figure 4-2. Effect of Vehicle Range on Vehicle Use - Percent of Random Miles Traveled, Inside SMSA, Personal Travel Only

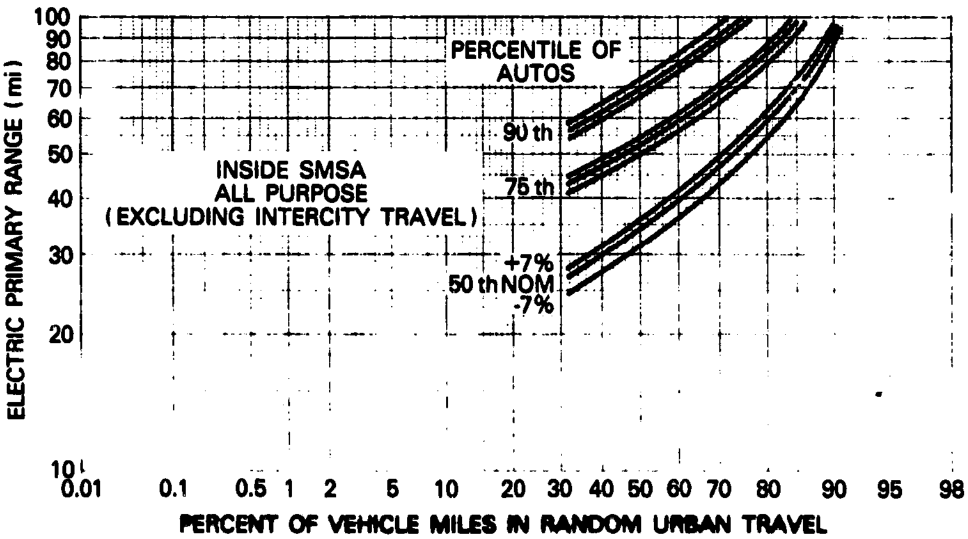


Figure 4-3. Effect of Vehicle Range on Vehicle Use - Percent of Random Miles Traveled, Inside SMSA, All-Purpose Travel (Excluding Intercity Travel)

on electricity ranging from 28 to 48%, which is much greater than ±7% around the nominal value of 40%. This means that the effect of changes in annual mileage is relatively small as long as the usage of the hybrid vehicle permits most of the urban driving (e.g., 75%) to be done on electricity, but once the percentage of miles on electricity falls below 50%, further increases in annual mileage result in a rapid decrease in the utility of the vehicle using electricity.

4.2 INITIAL VEHICLE COST

The most important factors in determining the initial cost of the hybrid vehicle are the specific costs of the electric drive

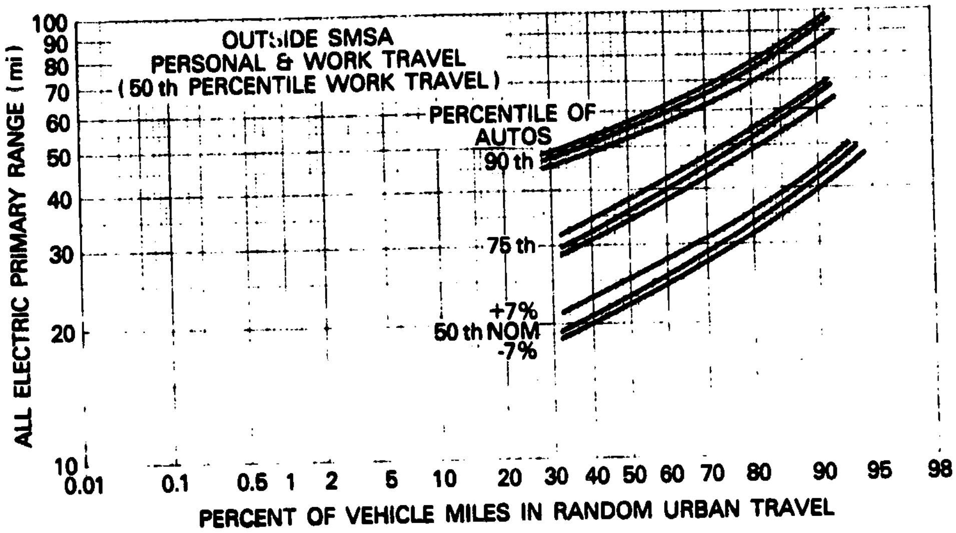


Figure 4-4. Effect of Vehicle Range on Vehicle Use - Percent of Miles Traveled, Outside SMSA, Personal Plus Work Travel

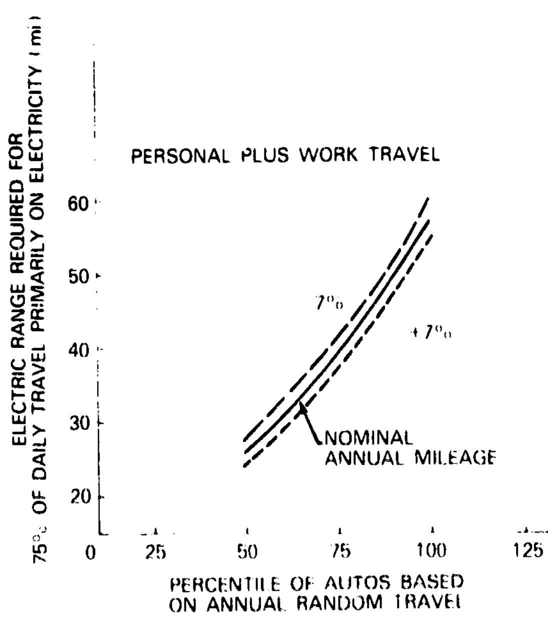
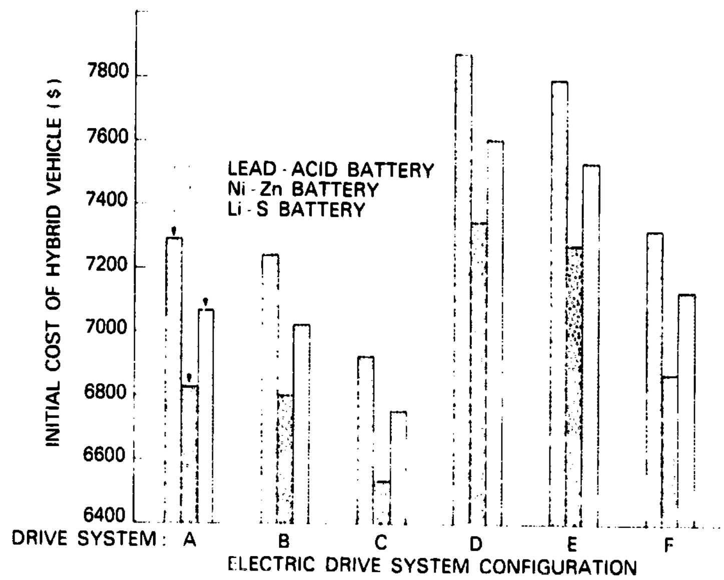


Figure 4-5. Effect of Changes in Annual Mileage on Electric Range Required

components and the batteries. As discussed in Section 3.2, the costs of the electric drive components (motors, controller, battery charger, contactors, etc.) are expected to be significantly affected by the volume at which these components are produced.

Thus, two production rates have been identified - low (100,000 units/yr) and high (1,000,000 units/yr). The latter production rate is comparable to that for components for conventional ICE vehicles in the United States. The sensitivity of the initial cost of a hybrid vehicle to battery type, electric drive-line components, and production rate is shown in Figure 4-6. The corresponding initial cost of the conventional ICE vehicle is $5700 in 1978 dollars. An examination of the effect of production rate on the initial cost of the hybrid vehicle shows that increasing the production rate from 100,000 to 1,000,000 units per year is projected to reduce the cost of the hybrid by $400 to $600 for all the battery and electric drive-line systems considered. This represents about a 33% reduction in the cost differential between the hybrid and conventional ICE vehicles.



DRIVE SYSTEM DESIGNATION:

A. High Volume, ac Motor and Inverter
B. High Volume, dc Motor with Armature and Field Control
C. High Volume, dc Motor with Field Control Only
D. Low Volume, ac Motor and Inverter
E. Low Volume, dc Motor with Armature and Field Control
F. Low Volume, dc Motor with Field Control Only

Figure 4-6. Sensitivity of Initial Cost of Hybrid Vehicle to Electric Drive System Components

The influence of the type of electric drive-line system (dc or ac) on initial cost is also shown in Figure 4-6. The ac drive system costs more than the dc drive system; the cost differential is $300 to $400 between the ac system and the lowest cost dc system using battery switching and field control to regulate the power from the electric motor. This latter dc system is the nominal system in the present study.

Battery type also affects the initial cost of the hybrid vehicle. Results are shown in Figure 4-6 for ISOA lead-acid, Ni-Zn, and Li-S batteries. For the battery cost inputs given in Table 4-1, hybrid vehicles using Ni-Zn batteries have the lowest cost followed by Li-S and lead-acid. The maximum differences in cost are about $500. The cost used for lead-acid batteries ($50/kWh) is quite realistic and probably attainable while for Ni-Zn ($60/kWh) and Li-S ($40/kWh) the cost values are more speculative. Whether they can be attained after further development of those batteries is open to some doubt.

Table 4-1

BATTERY COST AND LIFETIME CHARACTERISTICS

Battery Type	$/kWh	$/lb	Cycle Life
ISOA Lead-Acid	50	0.95	800
Ni-Zn	60	1.80	500
Ni-Fe	60	1.80	1500
Li-S	40	2.10	800

4.3 OWNERSHIP COST

The ownership cost of the hybrid vehicle is critical to its marketability because, as seen in Section 3, the initial expense of the hybrid vehicle is projected to be about $1200 to $1500 greater than that of the conventional ICE vehicle. Therefore, unless the ownership cost of the hybrid vehicle is lower than that of the conventional vehicle, potential car buyers would have little economic incentive to purchase the hybrid rather than the conventional vehicle. The sensitivity of ownership cost to a relatively large number of input parameters has been studied. The parameters considered include average annual mileage, fraction of miles in urban driving, electricity and fuel costs, vehicle lifetime and maintenance costs, general economic factors, and the cost of electric drive-line components (motors, controllers, and batteries). All the results given in this section are for gasoline engine-powered hybrid vehicles. A comparison of gasoline and diesel engine-powered hybrid vehicles is given later in Section 4.6.

The effect of average annual mileage on ownership cost (¢/mi) is shown in Figure 4-7 for annual mileages between 9500 and 12,750. Results are shown for hybrid vehicles using lead-acid, Ni-Zn, and Li-S batteries. The ownership cost of the reference ICE Vehicle is also given in Figure 4-7. The projected ownership costs of the hybrid vehicles are less than those of the conventional vehicle with the effect of annual mileage being nearly the same for all the vehicles considered. Annual mileage is seen to have a significant effect on ownership cost, but it does not affect the differences in ownership cost between the hybrid and conventional vehicles.

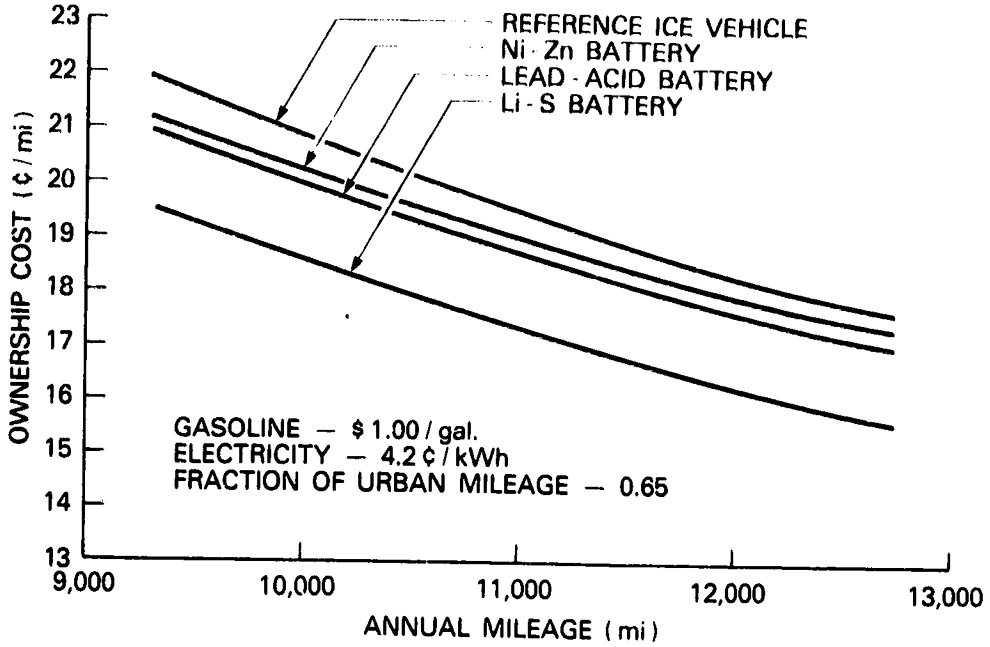


Figure 4-7. Effect of Annual Mileage on Ownership Cost

The sensitivity of the ownership costs of hybrid vehicles to the fraction of miles in urban driving is shown in Figure 4-8. In general, the ownership costs increase slightly as a greater fraction of the total annual miles are driven in urban areas. This same trend holds for the Reference ICE Vehicle because its fuel economy is lower in city driving than in highway driving. For the hybrid vehicles the ownership cost increases as more driving is done using electricity because the resultant decrease in battery life is only partly compensated for in energy cost savings (less gasoline and more electricity is used in urban driving). Figure 4-8 indicates that the ownership cost of the hybrid vehicle is less than that of the Reference ICE Vehicle and that the differences are essentially unaffected by the fraction of urban driving especially for lead-acid and Li-S batteries.

All the ownership cost results discussed thus far are for the nominal energy prices of $1.00/gal for gasoline and 4.2¢/kWh for electricity. The sensitivity of the ownership costs of the hybrid vehicles to energy prices is very important. The effect of electricity price on ownership costs is shown in Figure 4-9 for gasoline prices of $1 and $2 per gallon. It is seen that increasing the electricity cost from 2.5¢/kWh to 8.5¢/kWh increases the hybrid vehicle ownership cost by less than 1¢/mi. In addition, the ownership cost of the hybrid vehicle using lead-acid batteries remains less than that for the conventional vehicle until the cost of electricity reaches 8.5¢/kWh for a gasoline price of $1/gal. In essence, Figure 4-9 indicates that the price of electricity is relatively unimportant in determining the relative ownership costs of hybrid and conventional vehicles. The effect of gasoline price on the ownership cost of hybrid and conventional vehicles is shown in

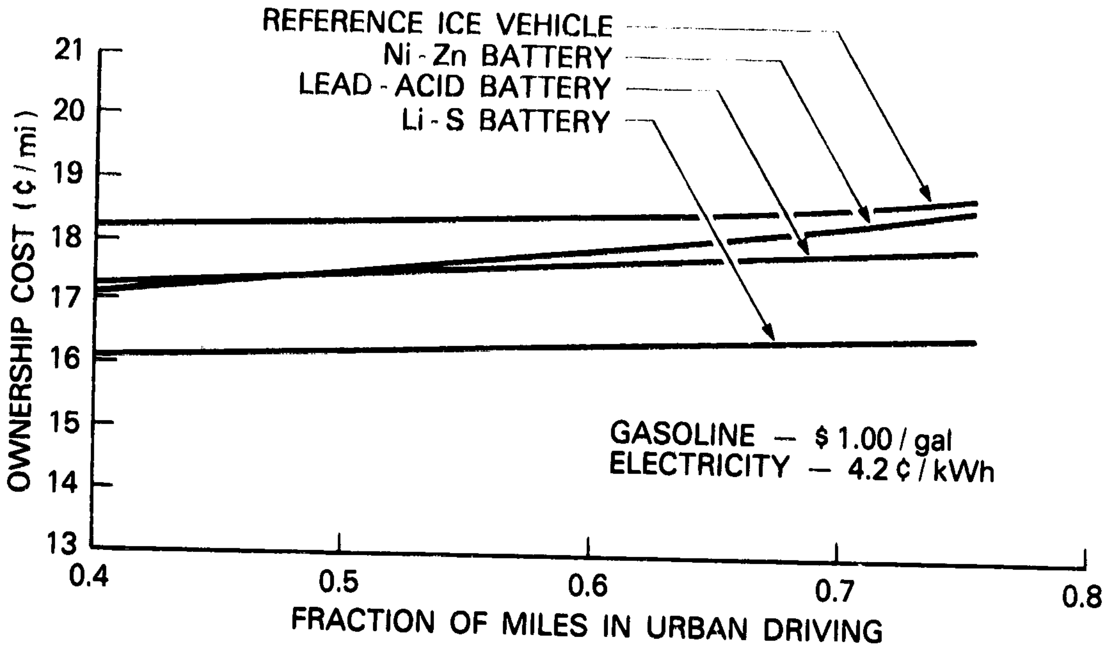


Figure 4-8. Effect of Urban Driving on Ownership Cost

Figure 4-10a through 4-10c. Results are shown for gasoline prices between 65¢/gal. and $2.50/gal. It is clear from Figure 4-10 that gasoline price has a large effect on the relative ownership costs of both types of vehicles. It is noteworthy that the differences in ownership cost begin to become significant at $1/gal and increase rapidly in the gasoline price range of $1 - $2/gal. The effect of electricity price is again seen to be quite small.

The result of extended lifetime and maintenance improvement on the ownership.cost of hybrid vehicles is shown in Figure 4-11 for vehicles using a gasoline engine and various types of batteries. The nominal assumption is that the hybrid vehicle has a lifetime of 12 yrs compared with 10 yrs for the conventional vehicle and has a maintenance cost of 25% less than the conventional vehicle. It is clear from Figure 4-11 that extending the lifetime and reducing the maintenance of the hybrid vehicle is an important factor in attaining ownership costs less than the conventional vehicle. For example, at the nominal energy costs of $1.00/gal for gasoline and 4.2¢/kWh for electricity, the ownership cost of the hybrid vehicle would be 19¢/mi compared with 18.5¢/mi for the conventional vehicle if both vehicles had a lifetime of 10 yrs and a maintenance cost of 2¢/mi.

The effect of general economic conditions on the ownership costs of the hybrid and conventional vehicles is shown in Figure 4-12. As would be expected, the ownership costs all increase (in constant dollars) as the inflation rate is varied between 3 and 10% per year. However, the relative effects on the various vehicles are small and do not seem to influence significantly the relative economic attractiveness of the hybrid and conventional vehicles.

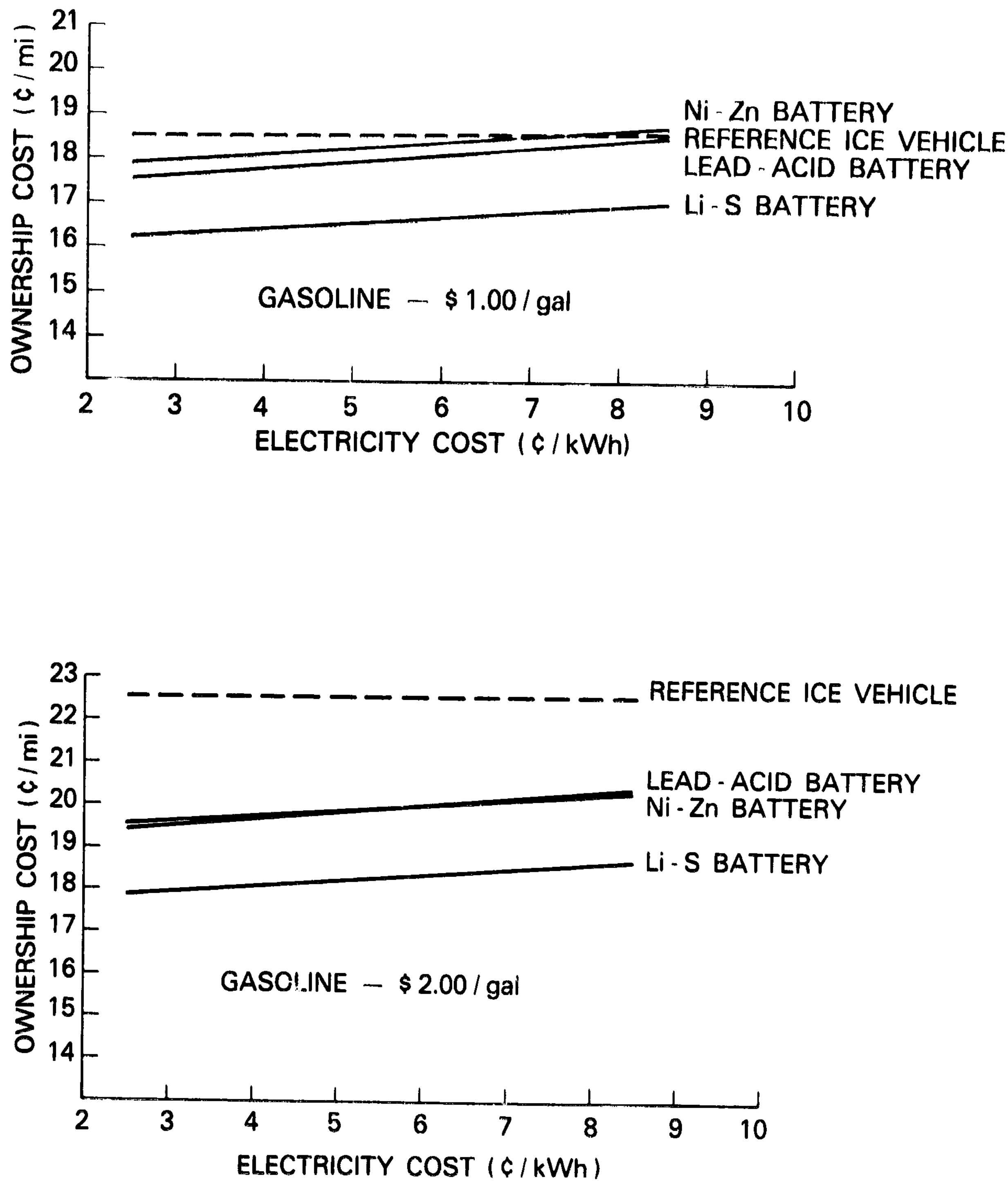


Figure 4-9. Effect of Energy Cost on Ownership Cost

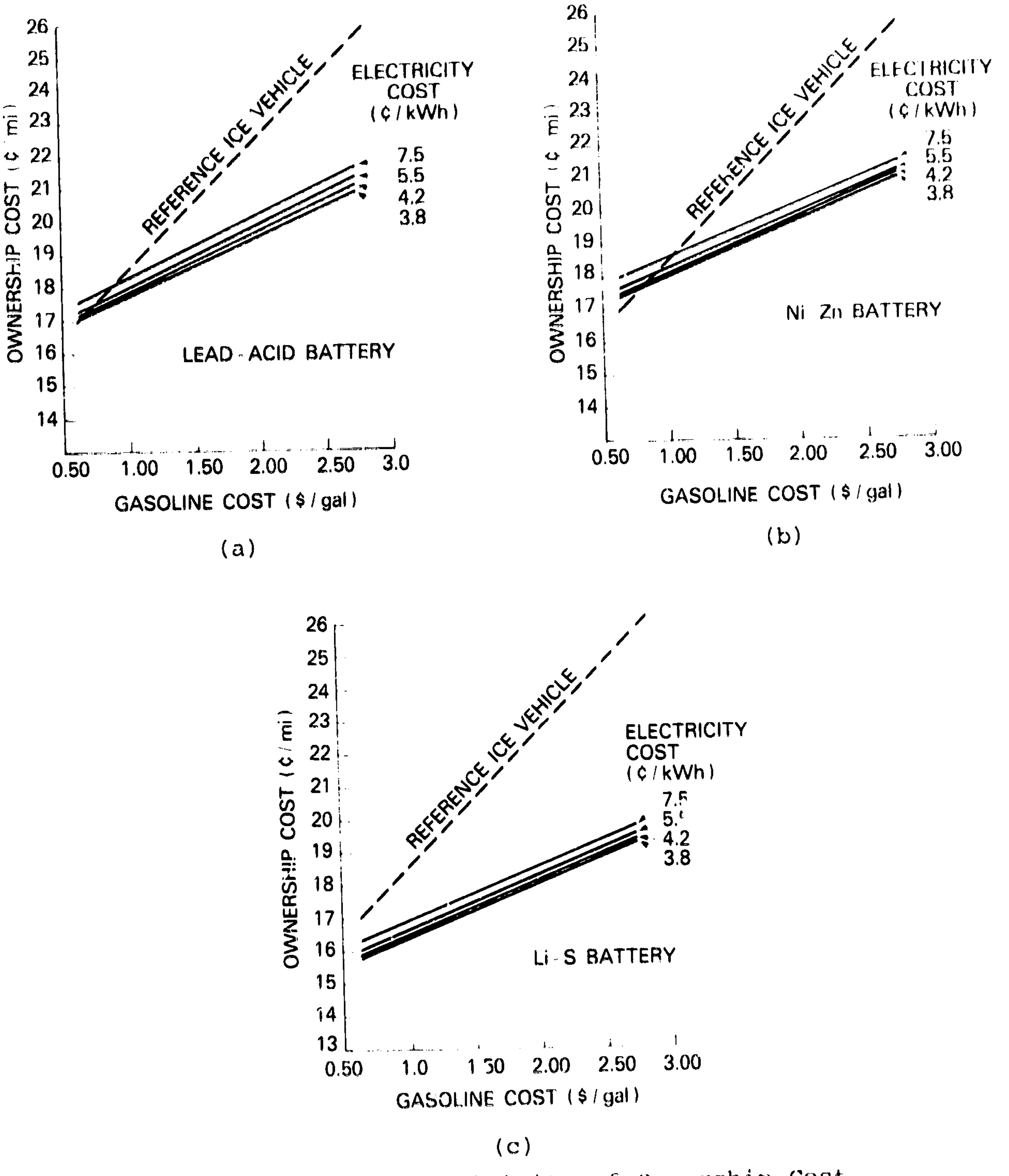
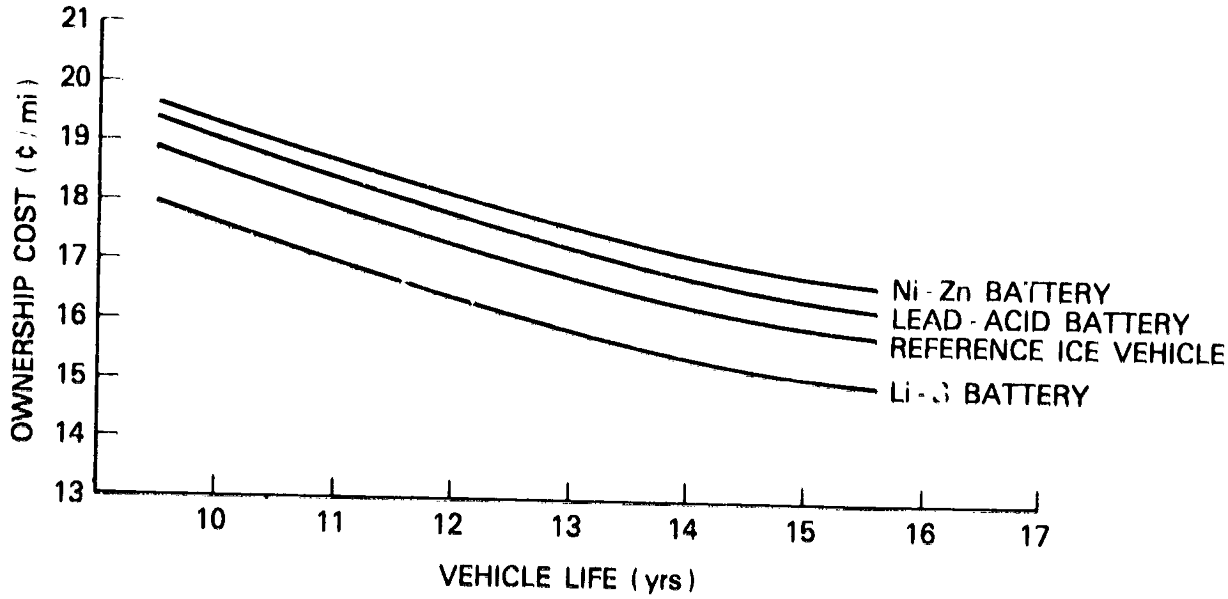
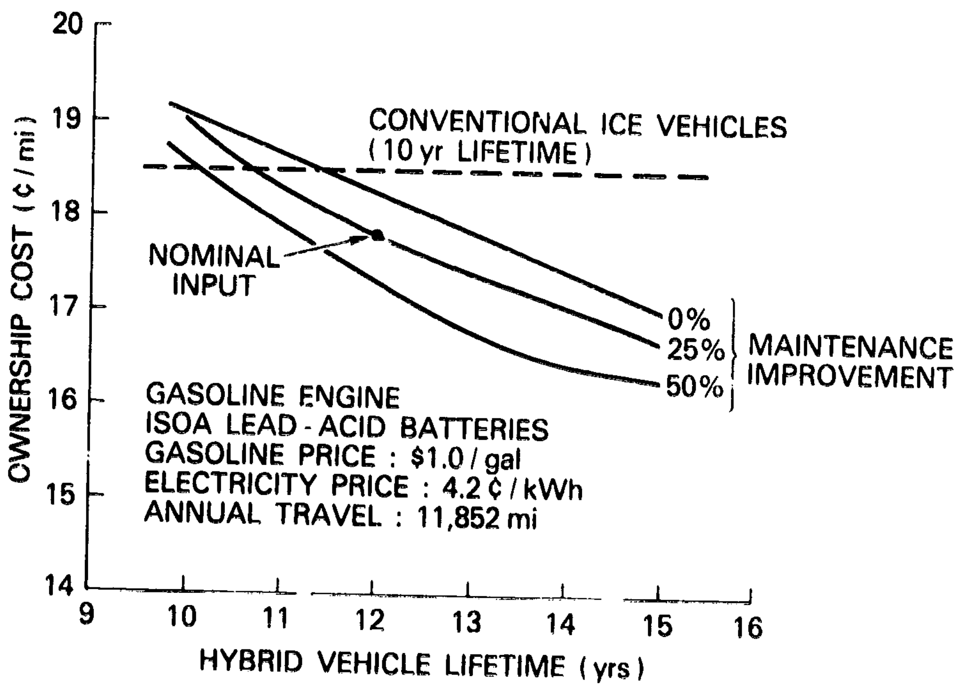


Figure 4-10. Sensitivity of Ownership Cost to Price of Gasoline



(a)



(b)

Figure 4-11. Effect of Extended Lifetime and Maintenance Improvement on the Ownership Cost of Hybrid Vehicles

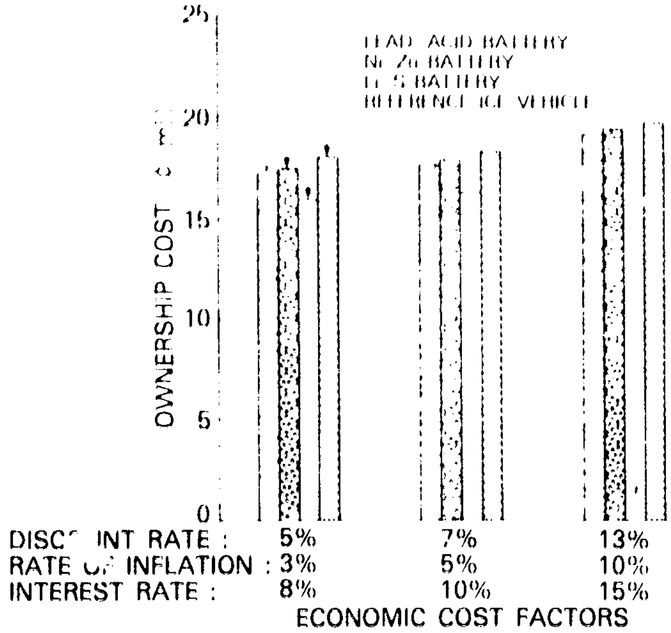


Figure 4-12. Sensitivity of Ownership Costs to Various Economic Cost Factors

The sensitivity of ownership cost to electric drive system component costs and production rates is shown in Figure 4-13. The effect is at most 1.5-2¢/mi for a specified battery type. This magnitude is not large but is significant when compared to the difference between the ownership costs of the hybrid and conventional vehicle at gasoline prices around $1/gal.

4.4 ANNUAL GASOLINE SAVINGS

The annual gasoline savings depend on the fuel economy characteristics of both the hybrid and the conventional ICE vehicles. It also depends on the way in which the vehicles are used. The total annual gasoline savings of the hybrid vehicle fleet is, of course, equal to the gasoline savings per vehicle multiplied by the number of vehicles in the fleet. The latter factor depends on market penetration, which is discussed in the next section.

The effect of annual mileage on gasoline saved per vehicle is shown in Figure 4-14. As would be expected, the gasoline saved (gal/yr) increases linearly with annual mileage. The savings resulting from the use of Ni-Zn and Li-S batteries are higher than those using lead-acid because the hybrid vehicles using the advanced batteries are lighter in weight.

The sensitivity of annual gasoline savings to fraction of miles in urban driving is given in Figure 4-15. The gasoline saved increases as more of the driving is done in urban areas because this permits the hybrid vehicle to utilize the electric drive system alone a greater fraction of the time. The fraction of the gasoline

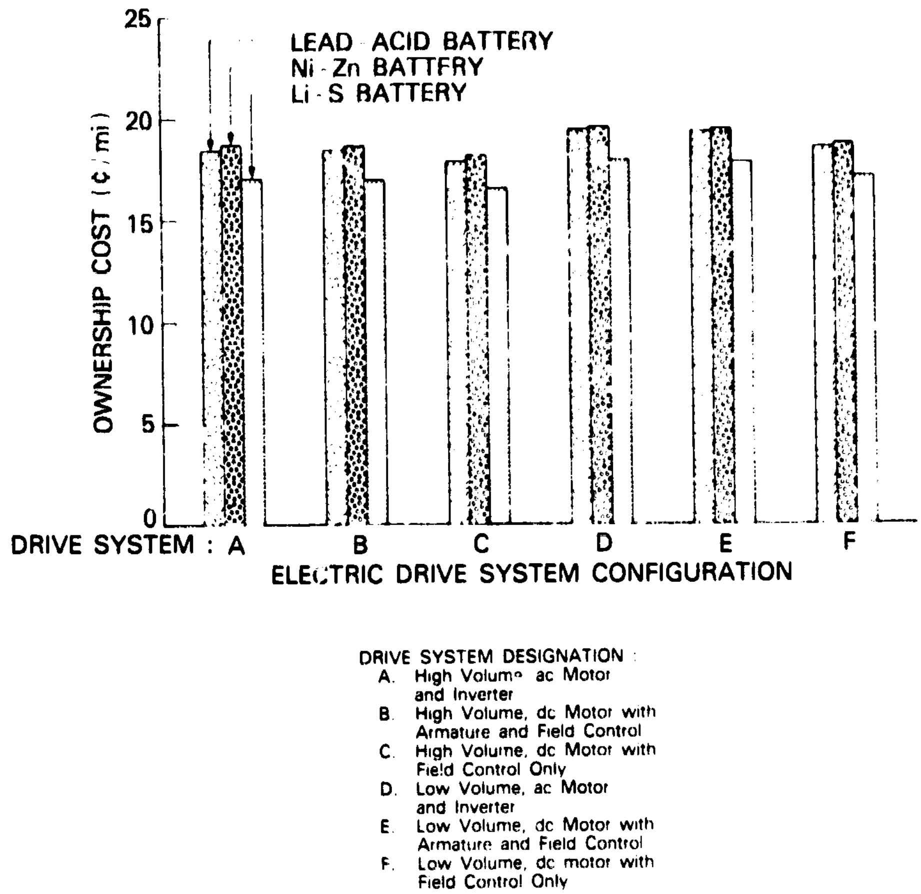


Figure 4-13. Sensitivity of Ownership Costs to Electric Drive System Components

saved compared to the Reference ICE Vehicle is obtained by dividing the gasoline saved by that used by the reference vehicle. For a nominal fraction of miles in urban driving of 0.65, a hybrid vehicle using lead-acid batteries would have a gasoline savings of about 53%.

The gasoline saved per year depends on the fuel economy of the Reference ICE Vehicle. As the fuel economy of the reference vehicle is improved, the potential gasoline saving is, of course, reduced. Annual gasoline savings using the hybrid vehicle are shown in Figure 4-16 for a range of fuel economies for the Reference ICE Vehicle. The first two sets of fuel economy (on the left) correspond to 1979 values (EPA-corrected and uncorrected) and the last two sets correspond to projected 1985 values for a five-passenger car. The projected EPA-corrected fuel economics (22 mpg-urban) and 32 mpg-highway) have been used as the nominal values in the present study. The gasoline savings would have been greater had the 1979 EPA fuel economy values been used for the Reference ICE Vehicle. Figure 4-16 shows the strong sensitivity of gasoline savings to the base-line fuel economy used for the Reference ICE Vehicle.

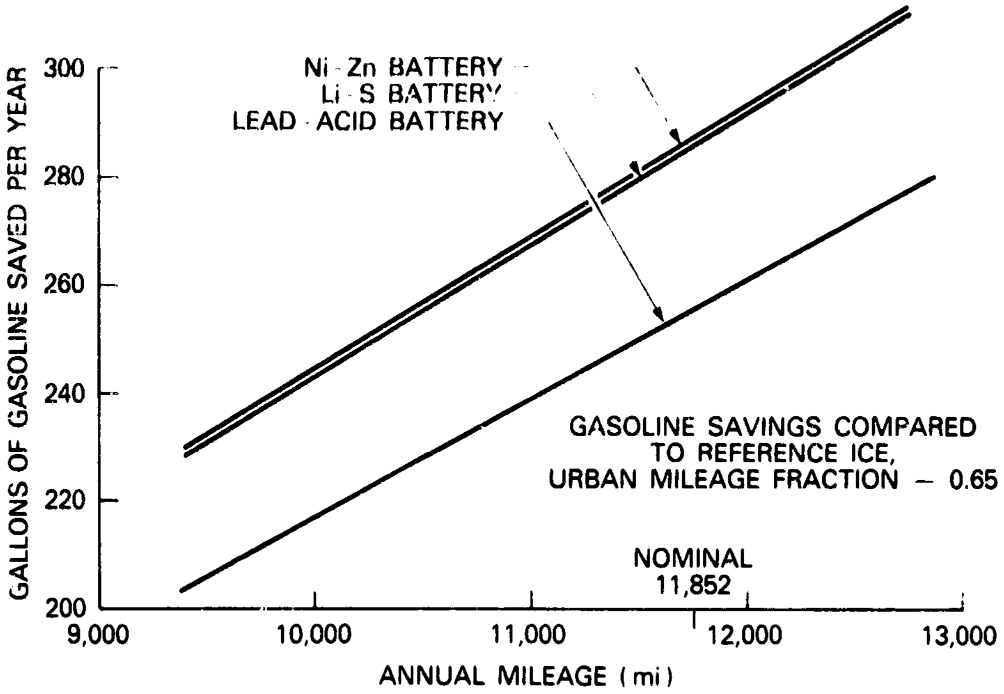


Figure 4-14. Sensitivity of Annual Gasoline Savings to Annual Mileage

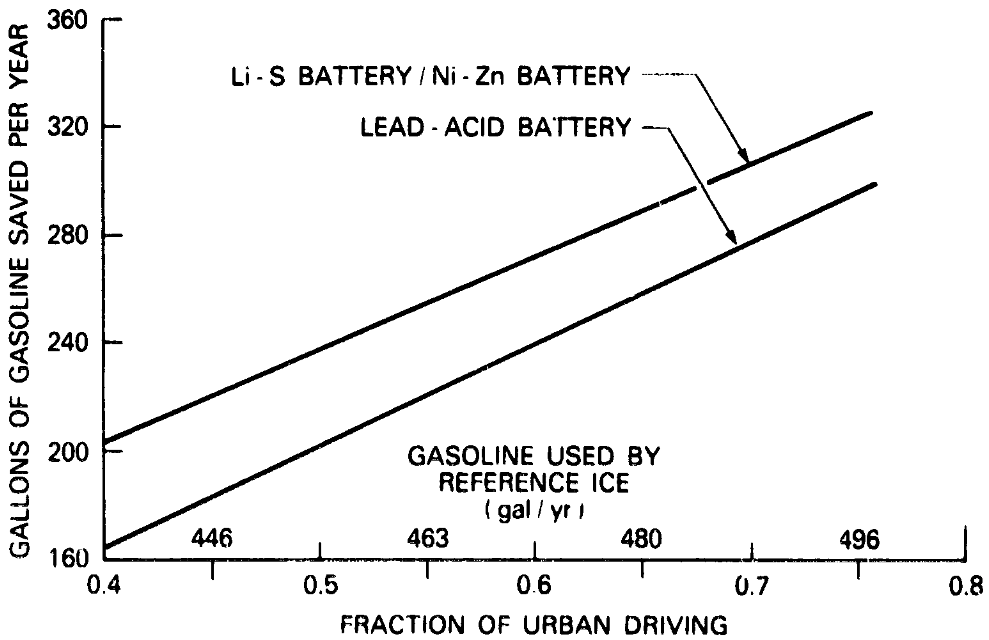


Figure 4-15. Sensitivity of Annual Gasoline Savings to Fraction of Urban Driving

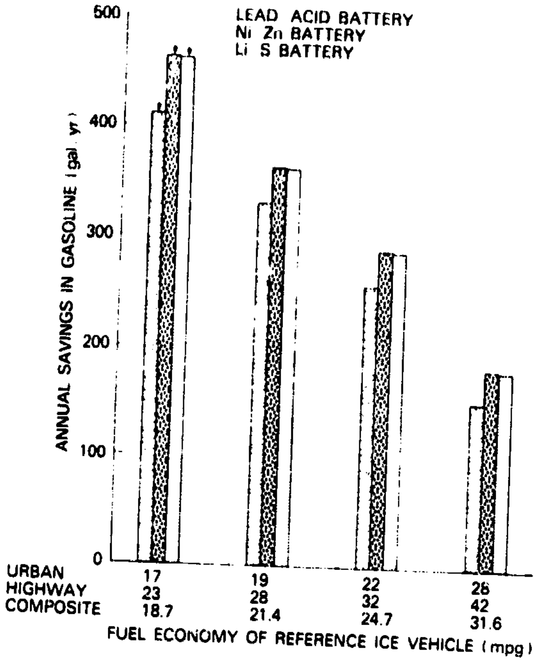


Figure 4-16. Sensitivity of Annual Gasoline Savings to Fuel Economy of Reference ICE Vehicle

4.5 MARKETABILITY CONSIDERATIONS

In order for the market penetration of hybrid vehicles to be significant, such vehicles must be economically attractive to a large fraction of potential car buyers. In addition, if significant market penetration is to lead to large annual savings of gasoline (millions of barrels per day), it is necessary that the fraction of gasoline saved be relatively high for most of the hybrid vehicles sold regardless of use pattern. These considerations were investigated by making computer calculations for daily travel statistics (see Section 3.1.1.3) representing cars/owners in the 35th to 90th percentiles of use based on annual mileage in random urban driving. The mission selected for this study was personal business plus to and from work travel. The total annual mileage (urban plus highway) ranged from 8571 for the 35th percentile to 14,715 for the 90th percentile of car owner. The combinations of inputs to the HYVELD program were selected to correspond to the 35th, 50th, 75th, and 90th percentile of car owners. The results of the calculations are discussed using the percentile of car owner as the independent variable. Variations with percentile will reflect the marketability of the hybrid to a wide spectrum of potential car buyers.

Ownership cost saving and fraction of gasoline saved results are given in Figure 4-17 for a hybrid vehicle having an electric range of 30 mi. The energy costs used for these calculations were \$1.00/gal for gasoline and 4.2¢/kWh for electricity. It is interesting to note from Figure 4-17 that the ownership cost saving of the hybrid vehicle compared with the conventional vehicle is nearly independent of the percentile of car owner even though the annual mileage and gasoline used by the conventional vehicle vary by nearly

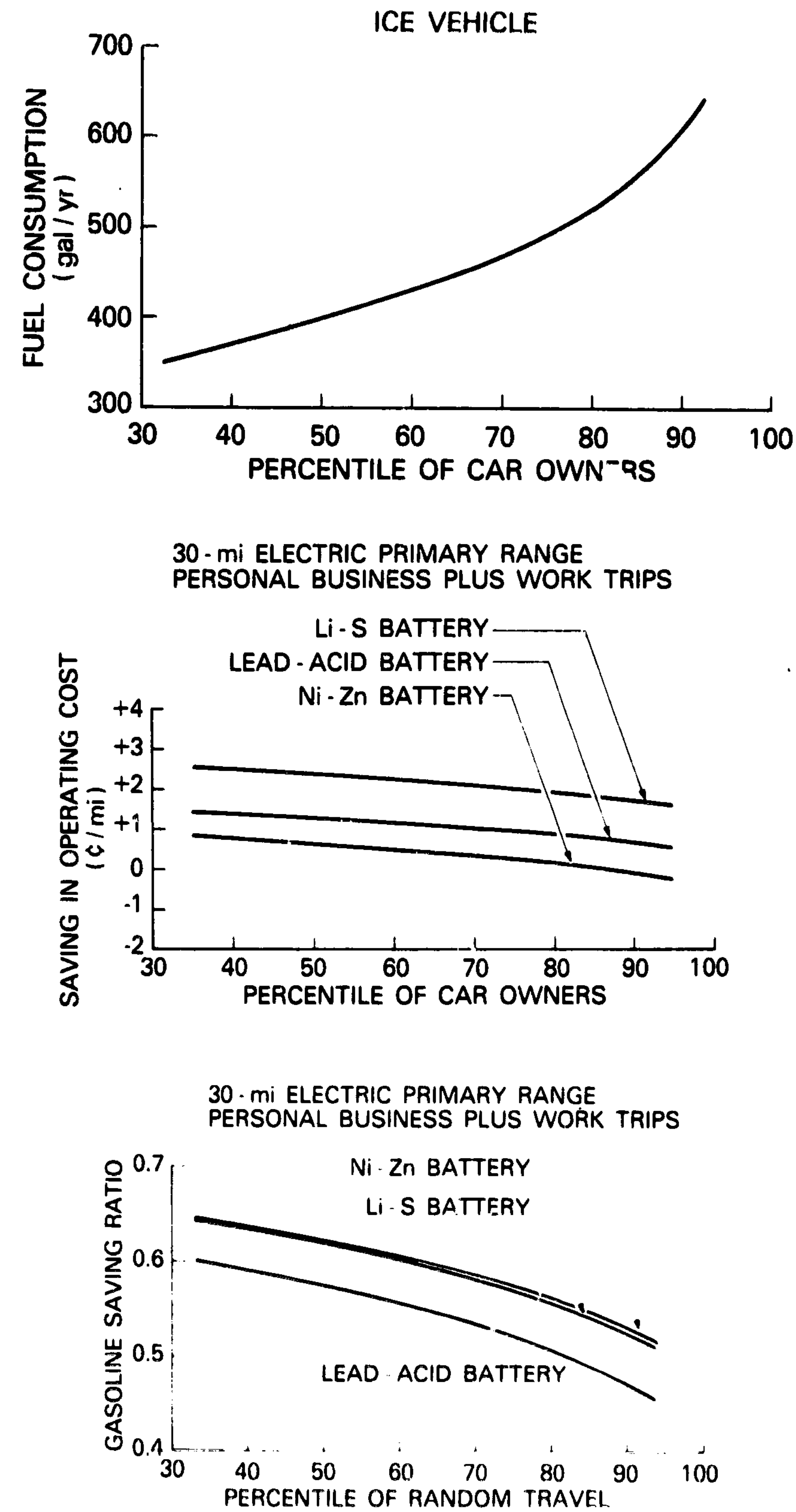


Figure 4-17. Effect of Battery Type on Fuel Saved and Ownership Cost

a factor of two. The fraction of gasoline saved varies from about 62% for the 35th percentile owner to about 50% for the 90th percentile. The corresponding gallons of gasoline saved per year are 215 and 305, respectively. The data given in Figure 4-17 indicate that the hybrid vehicle should be equally attractive to a large group of buyers and result in large gasoline savings for the entire group. Figure 4-18, based on the questionnaire data of U.S. News and World Report,(4) indicates that a vehicle must be attractive to new car buyers in a wide range of circumstances if it is to have good market penetration.

Calculations were also made to assess the effect of design electric range on the appeal of hybrid vehicles to a wide group of potential car buyers. Vehicle electric range was varied from 30 to 40 mi using the same daily travel statistics as were used in the previous marketability study. The results of the calculations are given in Figure 4-19. As expected, the ownership cost of the hybrid vehicle increases as its design electric range is increased because the battery weight, and thus its cost, is higher. This increase in ownership cost is relatively small -- only about 1¢/mi for a change in electric range from 30 to 40 mi. Also as expected, the fraction of gasoline saved increases for all percentiles of owners as the electric range is extended. The increase in gasoline fraction saved is only about 0.025 for the electric range change considered. Hence, one concludes that marketability and fraction of gasoline saved are not sensitive functions of electric range -- at least, in the neighborhood of the 30 mi nominal value used in the present study.

4.6 ENGINE TYPE -- GASOLINE AND DIESEL

Calculations were made to compare the ownership costs of hybrid vehicles using gasoline and diesel engines as a function of fuel price. The ownership costs of diesel engine-powered hybrid vehicles using various types of batteries are given in Figure 4-20. The ownership cost of the conventional diesel-powered vehicle is shown in the figure for comparison. A break-even diesel fuel price of about 60¢/gal is indicated for a hybrid vehicle using lead-acid batteries. At higher fuel prices, the hybrid vehicle shows a clear advantage in ownership cost compared to the conventional vehicle.

The ownership costs of gasoline - and diesel - powered vehicles are compared in Figure 4-21 and Figure 4-22. The hybrid vehicles all use lead-acid batteries. The diesel-powered vehicles have lower ownership costs, but, as indicated in Figure 4-22, the ownership cost savings is greater for gasoline engine-powered hybrid vehicles than for those using diesel engines. The differences in ownership cost are, however, quite small -- less than 1¢/mi.

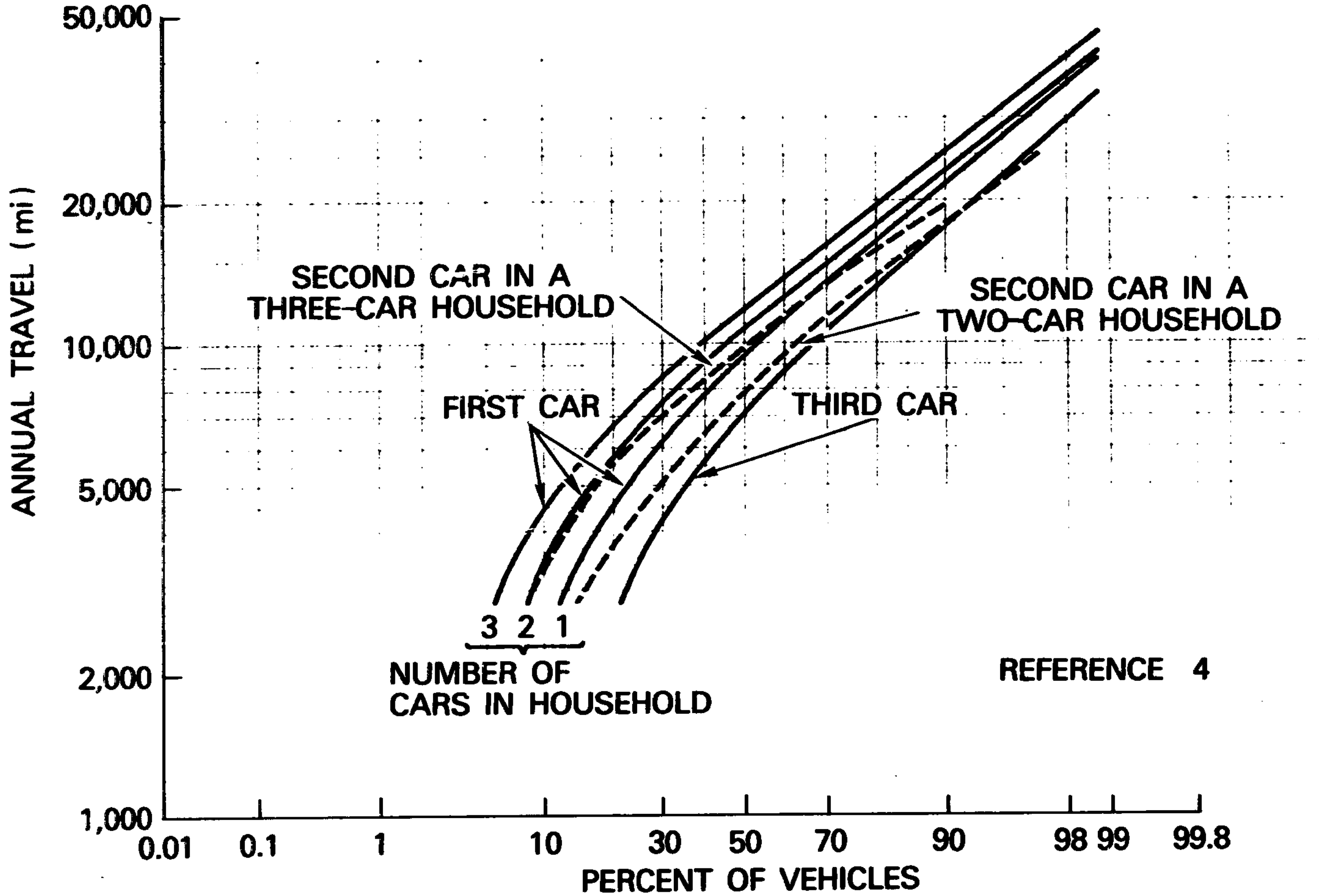


Figure 4-18. Annual Travel Characteristics for Multiple-Car Households

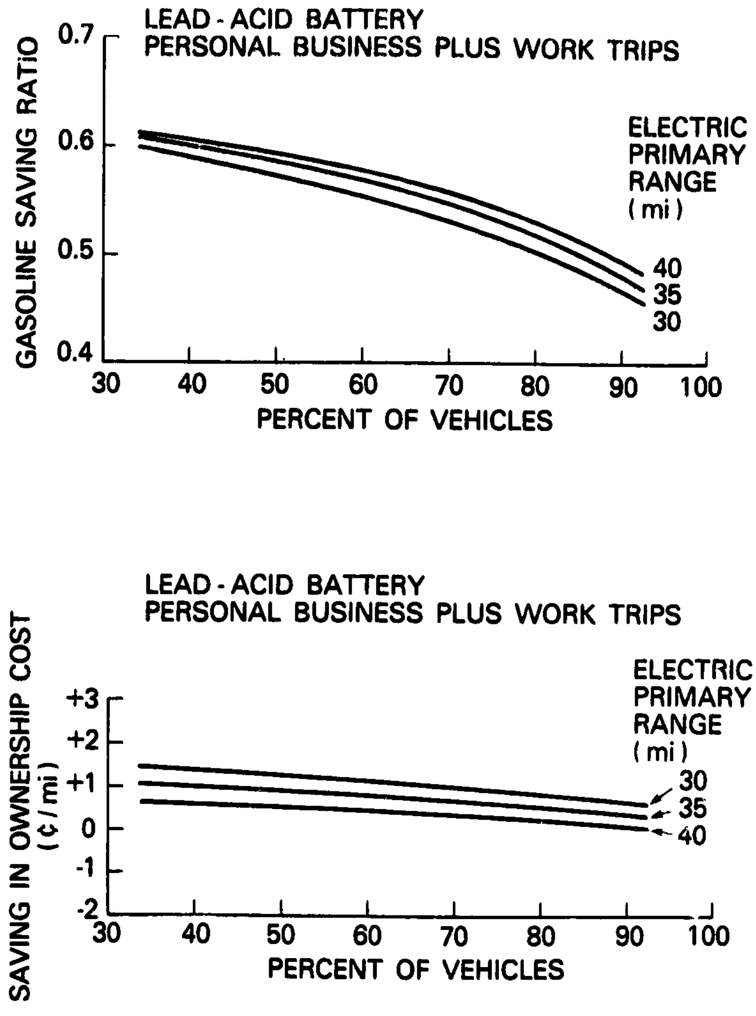


Figure 4-19. Effect of Electric Primary Range on Fuel Saved and Ownership Cost

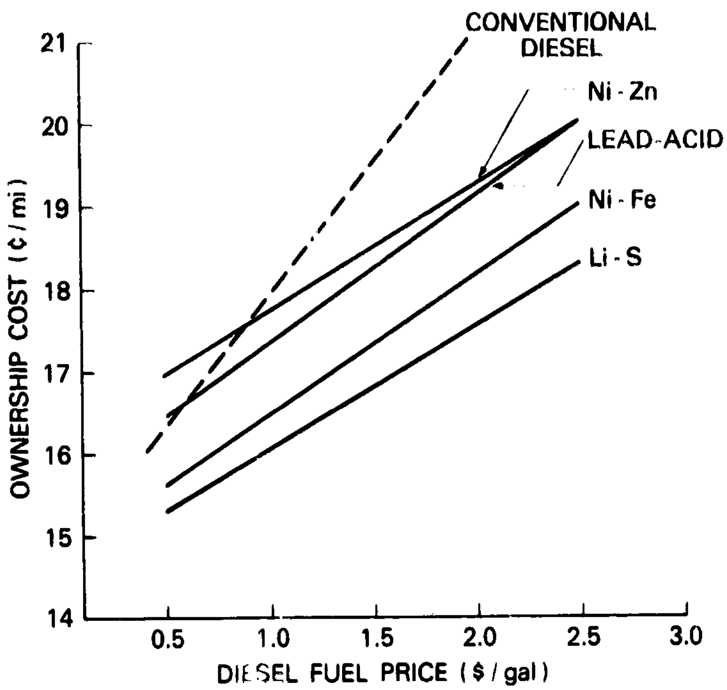


Figure 4-20. Effect of Diesel Fuel Price on the Ownership Cost of a Hybrid Vehicle for Various Types of Batteries

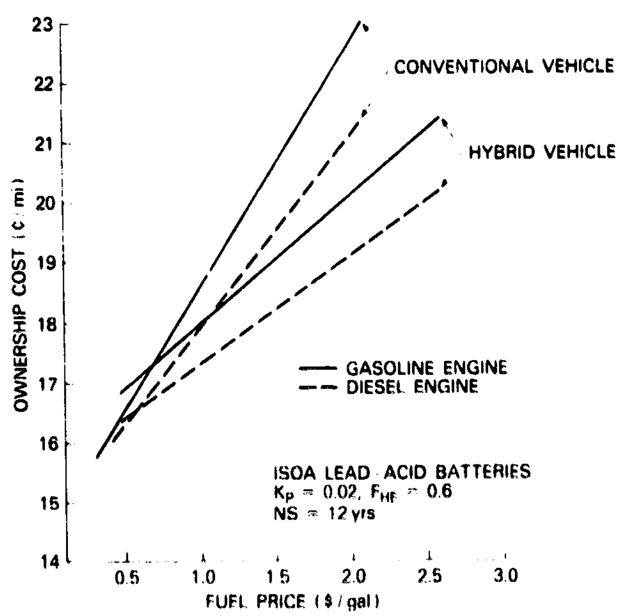


Figure 4-21. Comparison of Ownership Costs of Hybrid Vehicles Using Gasoline or Diesel Engines

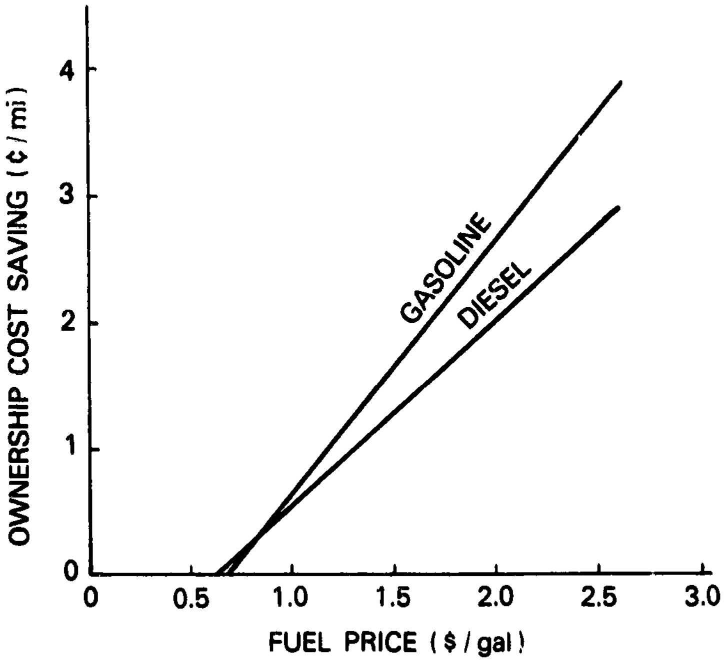


Figure 4-22. Effect of Engine Type on Ownership Cost Saving

Section 5

CONCLUSIONS

Section 5

CONCLUSIONS

5.1 INTRODUCTION

Parmetric studies were made using a hybrid vehicle synthesis and economics program (HYVELD) to investigate the sensitivity of hybrid vehicle cost, fuel usage, utility, and marketability to changes in travel statistics, energy costs, vehicle lifetime and maintenance, owner use patterns, ICE Reference Vehicle fuel economy, and drive-line component costs and type.

5.2 CONCLUSIONS

The major conclusions drawn from the sensitivity analysis are the following.

1. Changes in annual mileage are reflected directly in the fraction of the miles that the hybrid vehicle can be driven primarily on electricity with the marginal effect increasing rapidly when the fraction falls below 50%.

2. For the lowest cost dc electric drive system and high-volume production, the initial cost of the hybrid vehicle would be $1200 to $1500 higher than that of the conventional vehicle. This cost differential would be $1600 to $2100 for low-volume production of the electric components.

3. For nominal energy costs ($1.00/gal for gasoline and 4.2¢/kWh for electricity), the ownership cost of the hybrid vehicle is projected to be 0.5 to 1.0¢/mi less than the conventional ICE vehicle. To attain this ownership cost differential, the lifetime of the hybrid vehicle must be extended to 12 years and its maintenance cost reduced by 25% compared with the conventional vehicle.

4. The ownership cost advantage of the hybrid vehicle increases rapidly as the price of fuel increases from $1 to $2/gal. The effect of the cost of electricity on ownership cost is small for electricity prices between 2.5¢ and 8.5¢/kWh.

5. Annual mileage and fraction of miles in urban driving do not significantly affect the ownership cost differential between the hybrid and conventional vehicles.

6. Changes in general economic conditions (i.e., the inflation rate) do not significantly affect the ownership cost differential between the hybrid and conventional vehicles.

7. Annual fuel savings using the hybrid vehicle are strongly dependent on the fuel economy baseline used for the Reference ICE Vehicle. Using projected 1985 fuel economy values, the hybrid vehicle would have a fuel savings of about 55% or 250 gal per vehicle.

8. Hybrid vehicles would be economically attractive to a wide group of new car buyers with the ownership cost and fraction of fuel saved varying only slightly between the 35th and 90th percentile of car owners.

9. The economic attractiveness of the hybrid vehicle is not a strong function of design electric range for changes in range between 30 to 40 mi.

10. Hybrid vehicles using diesel engines have a slight advantage in ownership cost (0.5 - 1.0¢/mi) compared to those using gasoline engines, but the gasoline engine-powered hybrid has a slightly greater ownership cost differential advantage compared to the corresponding conventional vehicle.

Section 6

REFERENCES

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